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# **Collision Monitoring and Alarm in Ice-Hockey**

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<b>Abstract:</b>			
<p>Full contact sports are inherently dangerous as they involve tough collisions between players. Wireless and sensing technologies have the potential to reduce the risk of severe injuries in athletes by alarming the harshness of each collision between players to a medical team that can deal with this issue instantly, instead of allowing this hit to develop to a serious injury. Ice-Hockey is used as the basis of the experiment in this Master Thesis, since it is the highest contributor to brain injuries in sports and a source of devastating chest injuries.</p> <p>In order to achieve the goal of proposing and evaluating a sport safety system that can monitor and alarm the collisions between players to a medical team, several important questions were put to define the road-map of the research. Initially, a survey on the state-of-the-art sport safety systems has been made. The result of this survey shows that there is only one commercially available system: Head Impact Telemetry (HIT). Then, based on the study of HIT and its related products, several justified system requirements have been listed. Add to that, the applicable wireless and sensing technologies were benchmarked against the developed system requirements. This benchmarking resulted in selecting accelerometers and Bluetooth Low Energy (BLE) for the proposed system. In addition, a theoretical evaluation was made to the proposed system to find the Bit Error Rate (BER), Packet Error Rate (PER), average packet transmissions, average packet delay and packet loss percentage in AWGN, Rayleigh and Rician channels.</p> <p>The system evaluation results show that the proposed system with limited transmissions performs better than the system with infinite transmission attempts in both cases: no interfering users and one interfering user, over the stated channels. The limited transmission attempts system gives lower packet delay and less number of packet retransmissions. However, this limited transmission attempts system introduces packet loss. Also, it has been observed that small packet size selection reduces the latency and transmission attempts. Therefore, this system offers the Ice-Hockey community with a cost-efficient and reliable solution to the players' collisions monitoring and early diagnostic problem. Consequently, this may lead to reduction in total severe injuries and increased player career duration.</p>			
<b>Keywords:</b> Ice-Hockey, BLE, Collision Monitoring, SFH-GMSK			

## Preface

First of all, I would like to express my gratitude and appreciation to Prof. Riku Jäntti for his guidance, patience, support and mentoring throughout the Master Thesis period.

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## List of Abbreviations

AFH	Adaptive Frequency Hopping
AMP	Alternate MAC/PHY
ATT	Attribute Protocol
AWGN	Additive White Gaussian Noise
BC	Bluetooth Classic
BER	Bit Error Rate
BLE	Bluetooth Low Energy
BPSK	Binary Phase Shift Keying
BR	Basic Rate
B-SIG	Bluetooth Special Interest Group
BT	Bandwidth Time Product
CRC	Cyclic Redundancy Check
CSMA	Carrier Sense Multiple Access
DPSK	Differential Phase Shift Keying
DSSS	Direct Spread Spread Spectrum
EDR	Enhanced Data Rates
EU-27	European Union
FFD	Full Function Device
FHSS	Frequency Hopping Spread Spectrum
FSK	Frequency Shift Keying
FSR	Force Sensitive Resistor
GAP	Generic Access Profile
GATT	Generic Attribute Profile
GFSK	Gaussian Frequency Shift Keying
GMSK	Gaussian Minimum Shift Keying
HCI	Host-Controller Interface
HIT	Head Impact Telemetry
HS	High Speed
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IIHF	International Ice-Hockey Federation
ISM	Industrial, Scientific, Medical Frequency Band
ISI	Inter-Symbol Interference
LOS	Line-Of-Sight
L2CAP	Logical Link Control and Adaptation Protocol
LL	Link Layer
MAC	Medium Access Control
MSK	Minimum Shift Keying
NHL	National Hockey League
NLOS	Non-Line-Of-Sight

NWK	Network Layer
O-QPSK	Offset Quadrature Phase Shift Keying
OFDM	Orthogonal Frequency Division Multiplexing
PAN	Personal Area Network
PDU	Protocol Data Unit
PER	Packet Error Rate
PHY	Physical Layer
QoS	Quality-of-Service
RF	Radio Frequency
RFCOMM	Radio Frequency COMMunications Protocol
RFD	Reduced Function Device
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
RSS	Received Signal Strength
SAP	Service Access Point
SFH	Slow Frequency Hopping
SM	Security Manager
SNR	Signal to Noise Ratio
SRS	Side-line Response System
USB	Universal Serial Bus
UART	Universal Asynchronous Receiver/Transmitter
WBAN	Wireless Body Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

## List of Symbols

$T_c$	Coherence Time
$B_c$	Coherence Bandwidth
$B_s$	Doppler Spread
$\sigma_\tau$	RMS Delay Spread
$B_{C,50\%}$	Coherence Bandwidth with 50% Correlation
$T_{C,50\%}$	Coherence Time with 50% Correlation
$f_d$	Maximum Doppler Frequency
$f_c$	Carrier Frequency
$v$	Maximum Velocity of Player
$c$	Speed of Light
$T_s$	Symbol Duration
$P_b$	Bit Error Probability
$h$	Modulation Index
$d_{min}$	Minimum Distance
$\gamma$	Signal-to-Noise Ratio (Eb/No)
$\Gamma$	Average Signal-to-Noise Ratio (Eb/No)
$K$	Rician K-factor/ Ratio of Specular Power over Scattered Power
$\alpha$	Gaussian Filter Degradation Factor of Certain $BT$

$f_{\gamma}(\gamma)$	Fading Channel Distribution
$M_X(s)$	Moment Generation Function
$M$	Number of Frequency Channels
$K-I$	Number of Interfering Users
$N_{\text{bits}}$	Number of Bits in a Packet
$p$	Probability of Success
$q$	Probability of Failure
$n$	Number of Trials
$T_x$	Number of Transmission
$a$	Lower Limit of Truncated Probability
$b$	Upper Limit of Truncated Probability

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# **1 Introduction**

## **1.1 Background and Motivation**

Nearly 40 million injuries occur annually in the European Union (EU-27), of which 15 percent are sport related [1]. This means a staggering 16.5 thousand injuries occur every day because of practicing sports in the EU-27 region. More than half of these injuries are resulted from team sports which allow one-on-one contacts like Soccer, Handball and Ice-Hockey [2].

Ice Hockey is considered as one of the most dangerous team sports because it is the highest contributor for head injuries in sports with 28 percent share in the European Union [2] and overwhelming 44 percent stake in Canada [3]. Moreover, Ice-Hockey is also a source of some severe chest injuries like myocardial infarction and commotio cordis [4] [5]. These disturbing Ice-Hockey facts raise the question: How such severe injuries can be reduced or prevented?

In the last decade, there were many studies which tried to solve this problem. Studies [6], [7] and [8] have suggested the addition of new rules and the modification of existing rules to enhance the safety of the players. The main suggestions of these studies were to avoid body checking, eliminate fighting at all levels of ice-hockey participation and adding bonus points to the teams with minimal penalties. Other studies like [9] and [10] have proposed improving the sports gear used. These suggestions are logical and perhaps effective. However, these studies do not take into account the players' safety monitoring part. This is important because for this type of sports, the warrior spirit of the players prevents them from telling the medical team of their injuries during the games. Consequently, the impacts that the player receives during the game and other hits that could not be felt immediately can develop further showing symptoms of severe injuries [10].

As a result, this entails a need for an intelligent sensing system that is able to detect the severity of collisions between players, and then sending the gathered data to a medical team to deal with the issue instantly. Moreover, it is conceivable that this system may ultimately make considerable decrease in severe injuries, and eventually increasing the career duration of a player. Also, this intelligent sensing system promises reduction in costs to the teams, as players will be treated at an early stage of the injury.

## **1.2 Objectives and Related Research Questions**

The objectives of this Master Thesis are: to review the sport safety monitoring systems literature, to identify the related system needs, to conduct a provisional analysis of the characteristics and performance of the wireless technologies options and sensing methods, to

propose the architecture for the players' collisions monitoring and alarm system, and to perform a more detailed quantitative analysis of the selected wireless technology.

In order to achieve the stated objectives, the following main research questions need to be tackled:

1. What are the state-of-the-art designs for such similar sport safety monitoring systems? What are their advantages and disadvantages?
2. What are the system requirements?
3. What are the most promising sensing types that can be used to measure these collision impacts on the player's body?
4. What are the suitable wireless technologies that could be applied? How they should be graded?
5. What are the respective figures of merit for quality of the proposed system?

### **1.3 Contributions**

This Master Thesis discusses alternative solutions to a common problem in sports community which is "players' safety". It also introduces the application of Bluetooth Low Energy (BLE) with a cluster of sensors in sports safety. This can potentially decrease the risk of severe injuries to athletes.

In this Master Thesis, an Ice Hockey scenario is considered as the basis for the proposed system. However, this system can be modified to monitor the collisions occur to players in other dangerous sports.

### **1.4 Thesis Outline**

This Thesis consists of six chapters. In Chapter 2, a state-of-the-art survey is made for systems which offer the service of monitoring and alarming players' collisions. Moreover, this chapter states and justifies the requirements of an Ice-Hockey safety monitoring system. It also gives a provisional analysis on the applicable wireless technologies and sensors options. This chapter fully answers the first three research questions and partially the fourth one. Chapter 3 answers the fourth research question by benchmarking the possible wireless technologies for such impact monitoring and alarming system with the determined system requirements. This section will include an in-depth analysis of each technology. In Chapter 4, the proposed system architecture will be mentioned. Then, the wireless technology adopted will be analyzed further. This chapter answers the final research question. Chapter 5 will include an analysis of all the found results. Moreover, it will describe the performance of the actual application. Chapter 5 also answers the final research question. Finally, chapter 6 contains the conclusion and the expected future work.

## 2 Sport Safety Monitoring Preliminaries

### 2.1 Scenario Description

In an Ice-Hockey game, there are six active players per team. These players are continuously moving in an ice rink that has the dimensions of 30 m width by 61 m length [11]. The safety of these players is monitored by estimating the severity of impacts that occur to their heads and bodies. The severity of the impact is determined by a block of sensors fitted in the player's helmet and chest area of the shoulder pad. The sensor output data are sent to the medical team monitoring station by a Radio Frequency (RF) signals. This should be in real-time to allow the medical team to deal with concerning impacts quickly. This scenario is illustrated in Figure 1.

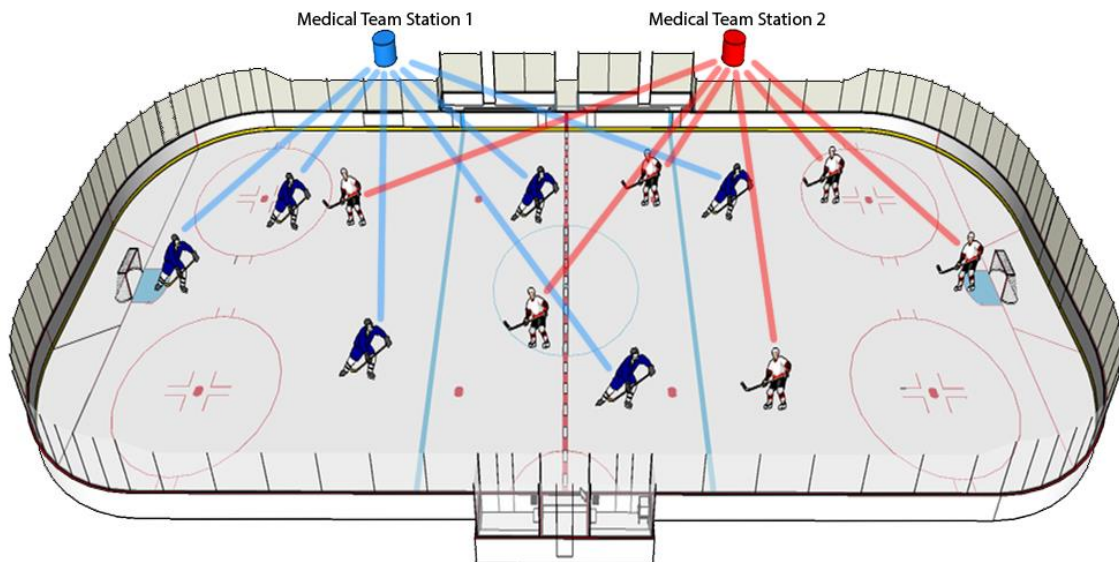


Figure 1 Monitoring Scenario

### 2.2 Head Impact Telemetry (HIT) System

Based on the scenario described in section 2.1, there is only one similar commercially available system. This system is called Head Impact Telemetry (HIT) [12]. HIT system is a sport safety monitoring system designed specifically for American football athletes. HIT system has been developed by researchers at Virginia Polytechnic Institute and Dartmouth College [13]. Currently, some Riddell's helmets [14] use this technology by employing Simbex sensors [12]. This HIT system is used in both Riddell Sideline Response System (2.2.1) and Riddell InSite (2.2.2) [15].

## 2.2.1 Riddell Sideline Response System (SRS)

### 2.2.1.1 Overview and Technical Details

Riddell SRS is the first commercially available system that can measure head impacts in real-time. Riddell SRS system (see Figure 2) is constructed by several player units communicating with a sideline receiver and a computer system via RF signals [16]. In details, each player unit is formed by a sensor block containing 6 linear accelerometers and 1 temperature sensor. This sensor block is connected to a wireless transceiver operating in the 903 to 927 MHz band [16]. Moreover, this player unit has an on-board microprocessor that contains a memory that is capable to record up to 120 impacts, with 8 bit data acquisition and 1 kHz sampling [16]. This whole player unit is fitted inside an American football helmet.



Figure 2 Riddell SRS HIT system [17]

In Riddell SRS system, when any single accelerometer detects an acceleration that exceeds a user-specified threshold (default 10 g), the data are collected for 40 ms. The system ensures collecting the entire impact waveform by storing 12 ms of pre-trigger data and storing 28 ms of post-trigger data [16]. In addition, a single sideline controller can monitor up to 64 players simultaneously [15]. The HIT system produces reports on the time of impact, location of impact, and severity of impact. In Table 1, the mentioned features are listed with information about the price of this system.

Monitoring Capability	Head Only
Target Market	American Football
Price	Starting from 370 USD to around 1000 USD per helmet [14], sideline receiver and laptop cost around 30k USD [13]
Impact Trigger	User specific, default=10g
Data Collection Time	40 ms
On-board memory	120 impacts
Sensors	6 linear accelerometers and 1 temperature sensor
Range	Covers an American football pitch
Maximum number of monitored players	64

Table 1 Summary details of Riddell SRS system

### 2.2.1.2 System Limitations

The Riddell SRS is designed only for American football. This makes it less versatile and hence, it cannot be used for other dangerous games like Ice-Hockey. Moreover, it only monitors the head impacts, while the body impacts are neglected. Another disadvantage of Riddell SRS is the price. A typical investment for a team of 40 players will cost between 44800 to 70000 USD depending on the helmet they choose. This high price might discourage many teams from adopting this solution.

Advantages	Disadvantages
User specified threshold	Expensive
Relevant alarms	It is only for American Football
Good range	Head impacts monitored only
64 players can be monitored simultaneously	

Table 2 Advantages and disadvantages of Riddell SRS system

## 2.2.2 Riddell InSite

### 2.2.2.1 Overview and Technical Details

Riddell InSite (see Figure 3) is another commercially available system that can measure head impacts in real-time [12]. Riddell InSite system is constructed of a player unit which is basically a five-point sensor pad that should be inserted inside a helmet and an alert monitor which is a small radio handheld device that receives alerts from the player unit(s) [18]. The alert monitor device can serve up to 150 players [15].



Figure 3 Riddell InSite HIT system [19]

Monitoring Capability	Head Only
Target Market	American Football
Price	\$150 per Player Unit and \$200 for the Alert Monitor [19]. It does not include the helmet.
Impact Trigger	Research specific [18]
Data Collection Time	40 ms
On-board memory	120 impacts
Sensors	5 linear accelerometers
Range	Covers an American football pitch
Maximum number of monitored players	150

Table 3 Summary details of Riddell SRS system

### 2.2.2.2 System Limitations

The Riddell InSite solution is designed for American football helmet. This makes it less versatile and hence, it cannot be used for other dangerous games like Ice-Hockey. Moreover, this solution is directed toward the youth, high-school and college level players but not the professionals [15]. Riddell InSite does not allow the user to adjust the impact threshold for each player like Riddell SRS [12] [15] [18]. However, the thresholds are based upon the position played and level of experience [18]. Finally, like the Riddell SRS, Riddell InSite only monitors head impacts, while the body impacts are neglected.

Advantages	Disadvantages
Price	No user specified threshold
Relevant alarms	It is only for American football
150 players can be monitored simultaneously	Head impacts monitored only
Good range	

Table 4 Advantages and Disadvantages of Riddell SRS system

## 2.3 Proposed System Requirements

### 2.3.1 Justification of System Requirements

From the previous section 2.2 describing the existing sport safety monitoring systems, it has been noticed that both Riddell SRS and Riddell InSite pose some advantages and disadvantages. Therefore, the requirements of the proposed system should adopt the advantages and solve the disadvantages of these systems. This will ensure that the proposed system is an improvement.

These discussed systems have many advantages such as providing relevant alarms like time of impact, severity of impact and impact location. Therefore, the proposed system should be able to provide this information. This implies that the sensors should be able to measure severe impacts which can be up to 100 Kg or 100 g [16].

Another advantage of these solutions is that they have a good data communication range (140 m) to cover the American football pitch. Therefore, an important requirement is to have a communication system that is able to send data all around the ice rink.

Furthermore, these systems can monitor many players concurrently. This is beneficial when there is a requirement for both teams to be monitored by one medical team. As a result, another requirement should include that the telecommunication system used should be able to handle many devices at once.

In addition, the communication system used should be able to have a suitable throughput to meet the demand of the application. Another requirement of the communication system used is to be able to send data in busy environment and/or be able to mitigate interference from systems co-existing in the same spectrum. This communication system should also be power efficient to enable continuous monitoring of players without frequent battery change.



Moreover, the player units of these systems are small in size as they are able to fit inside American football helmets. Therefore, another requirement should be related to the size. The size of the electronic devices on the player should not affect the players' movements.

Also, both systems gather the impact data for about 40 ms (12 ms pre-trigger and 28 ms post-trigger). Therefore, it can be assumed that the impact will reach to the medical team after 28 ms if there is negligible delay. Thus, the minimum packet delay for the proposed system should not exceed 28 ms.

In addition, Riddell SRS and Riddell InSite systems are using a network size based on the number of players plus the medical team monitoring station. Hence, the communication network size should not be larger than the number of players plus the medical team monitoring station.

It is clear that Riddell SRS is expensive since some teams with 30 players had to pay around 60000 USD to use the system [13]. On the other hand, it can be noticed that the price of Riddell InSite is actually good when considering that teams with 30 players can purchase the system for 4700 USD ( $30 \times 150 + 200$ ). This brings a huge reduction of price by a factor of 12.7. Therefore, the cost of the system should be at most 4700 USD.

Also, it is obvious that Riddell InSite is missing the great feature of allowing medical team to set a specific impact threshold for players [18]. Hence, another requirement is to allow the medical team to specify the impact threshold for each player.

Finally, these systems are concerned with the head impacts while there is no concern on the chest area, despite the fact that hard blows to the chest can cause myocardial infarction or commotio cordis [4] [5]. Therefore, the chest area needs to be monitored as well.

### **2.3.2 Summary of System Requirements**

The discussed system requirements can be simplified to the below:

- Provide relevant alarm information like: time of impact, location of impact and severity of impact.
- The communication range should be able to cover the whole monitored area. In Ice-Hockey, the range should be at least 61 meters.
- The medical team station should be able to monitor all the active players simultaneously. The communication system should allow the master transceiver to monitor the 6 active Ice-Hockey players continuously.
- The size of the electronics on the players should be small enough to be embedded in their helmets and shoulder pads.
- The minimum packet delay should be less than or equal to 28ms.

- The network size should be restricted to the number of equipped players plus the medical team station.
- The cost of the system should not exceed 4700 USD to allow teams to adopt the system with minimal investment.
- Allow a user-specific threshold for each player.
- The communication system should be reliable standard and power efficient.
- The communication system should have a decent throughput.
- The head and the chest area of the player should be monitored.

## **2.4 Applicable Wireless Technologies**

After determining the system requirements, several well-known wireless technologies appropriate for the proposed application have been described in the following sections.

### **2.4.1 Bluetooth IEEE 802.15.1**

Bluetooth is a wireless technology standard that was developed by Ericsson in 1994 [20]. Bluetooth is used for short range data exchange. Hence, the basic aim of its design was to replace short range wire connections. These ranges fall into the Wireless Personal Area Network (WPAN) ranges, which are from 10 meters to 150 meters [21]. In 1998, a cluster of Information and Communication Technology (ICT) companies have formed the Bluetooth Special Interest Group (B-SIG). This group still manages the Bluetooth technologies and standards [22].

Bluetooth technology occupies the 2.4 GHz Industrial, Scientific and Medical (ISM) band [21]. The number of channels and their bandwidths differ depending on the Bluetooth version; as will be discussed in later sections. The basic modulation technique used is the Gaussian Frequency Shift Keying (GFSK). In addition, Frequency Hopping Spread Spectrum (FHSS) is used on top of the modulation to decrease the interference caused by other devices and systems operating in the same ISM band [22]. Bluetooth is based upon star network topology [21]. This is done in order to eliminate the chances of internal data transmissions collisions. Usually, this is done by a Pico-net containing a Master that communicates with several Slaves based on time slots assignment.

Bluetooth has four versions and they are Bluetooth V.1, Bluetooth V.2 Basic Rate (BR) + Enhanced Data Rate (EDR), Bluetooth V.3 High Speed (HS) and Bluetooth V.4 Low Energy (BLE). The first Bluetooth version was released in the end of 1999. This technology was adopted by very few manufacturers since it was still not matured and had many faults, such as: low security, slow link establishment and low Quality of Service (QoS) [23]. In the year 2001, Bluetooth V. 1.1 was introduced to correct many errors and problems of V1.0. In addition, this

version included the Received Signal Strength Indicator (RSSI) which is used for measuring the power level in the received radio signal [23]. This version has become an approved standard with specified Medium Access Control (MAC) and physical layers in the Institute of Electrical and Electronics Engineers (IEEE) Standard 802.15.1–2002 [24]. After that, V1.2 was introduced in 2003 with more performance enhancements features such as faster discovery of nearby Bluetooth devices, signal quality based device sorting, faster connection establishment, Adaptive Frequency Hopping (AFH), and a new security functionality called “anonymous connection establishments” [25]. Finally, this version has become an approved standard in IEEE Standard 802.15.1–2005 [25]. In 2004, Bluetooth V.2 BR+EDR standard was released [23]. This version’s aim was to improve the physical layer of Bluetooth in order to achieve higher data rates. Accordingly, the version offers the BR of transmission which is 1 Mbps using GFSK modulation, and the EDR which is 2 Mbps using  $\pi/2$ -DPSK or 3 Mbps using 8-DPSK modulations. Therefore, this enables data rates to increase by the use of additional modulation techniques [20] [22]. In 2007, B-SIG has approved version 2.1 which promises new features related to security, better connections and lowering the power consumption [23].

Bluetooth V3 High Speed (HS) was released in 2009. This technology has provided many new improvements related to the MAC and the physical layers. However, the most notable one is the Alternate MAC/Physical (AMP) which allows the use of 802.11 MAC and physical layers for transporting Bluetooth profile data [23]. As a result, this technology requires minimal utilization of power and time since data can be transferred at high data rates from 3 to 24 Mbps. Bluetooth HS has the ability to dramatically prolong battery life as this technology only utilizes power after it has been activated until the transmission is terminated [21]. In addition, this version can be used for video streaming and huge data transmission if supporting AMP exists like Wi-Fi [26]. Finally, the range of this technology is only 10 meters.

The discussed Bluetooth versions have the same protocol stack architecture. This stack is built from the application layer, the middleware layer and the transport layer (See Figure 4).

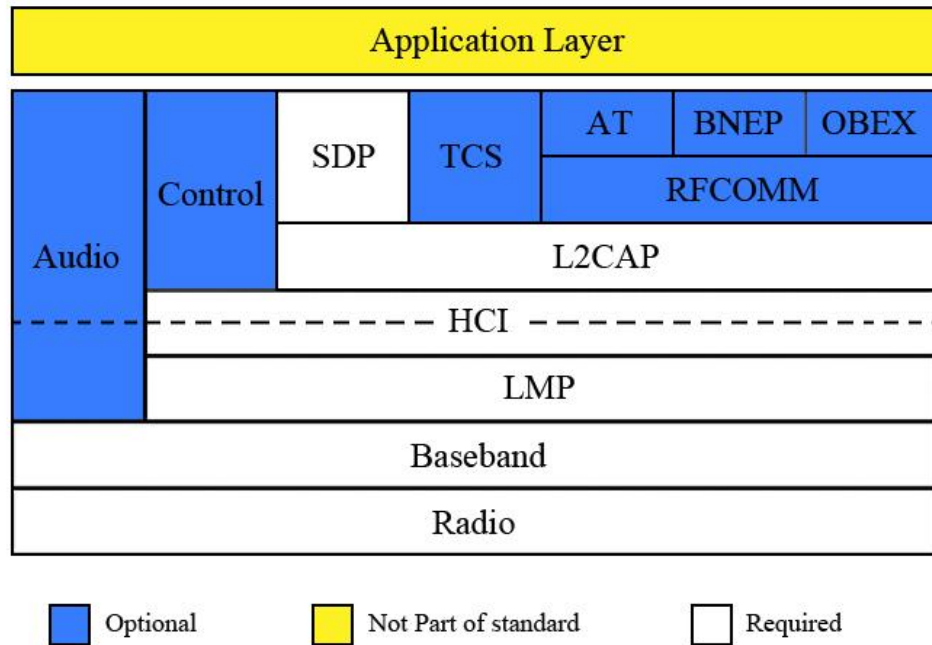


Figure 4 Bluetooth Protocol Stack (modified [23])

The application layer hosts all the external applications (Apps). The middleware layer consists of the different controls and protocols that allow communication with other Bluetooth devices. The Radio Frequency COMMunications protocol (RFCOMM) provides a serial communication channel on top of the Logical Link Control and Adaptation Protocol (L2CAP) [23]. L2CAP performs packet segmentation and reassembly. Host Controller Interface (HCI) is the interface between the middleware layer and the transport layer. The transport layer is formed by the Link Manager Protocol (LMP), baseband layer and radio physical layer. LMP is responsible for establishing connections and maintaining them with a certain quality [22]. Baseband layer controls voice and data channels [23]. Finally, the radio layer transmits a frequency hopped signal (1600 hops/sec) over 79 channels of 1MHz bandwidth [22].

On the other hand, Bluetooth V.4 Low Energy (BLE) was released in 2010 and it is considered to be a completely renewed Bluetooth standard [21] [27]. This technology is designed to be a serious competitor to ZigBee [21]. It has ultra-low power consumption, decent data rates (up to 1 Mbps), only 40 channels since each channel is 2 MHz, low cost and few milliseconds required for synchronization unlike older versions which may take couple of seconds [27]. BLE is known to have two implementation alternatives: stand- alone and dual-mode. Stand-alone chips are mainly used in sensors or actuators deployments, where the BLE devices only communicate among themselves, whereas the dual mode chips can be used to communicate with other Bluetooth devices containing older versions [28]. The major differences

of BLE compared to other Bluetooth technologies are in their radio transceivers, baseband digital signal processing, and data packet format since this technology uses an entirely new protocol stack. However, BLE is similar to other previous Bluetooth technologies in terms of short range communication and star-configured networks. This technology is assumed to be ideal for Body Area Network (BAN) applications or any application that do not exceed the range of 100 meters [21] [27].

As mentioned earlier, the protocol stack of BLE is entirely new and it is constructed as shown in Figure 5. BLE protocol stack size is very small when compared to Bluetooth classic's protocol stack [29]. Therefore, the complexity was reduced to allow efficient energy sensing applications.

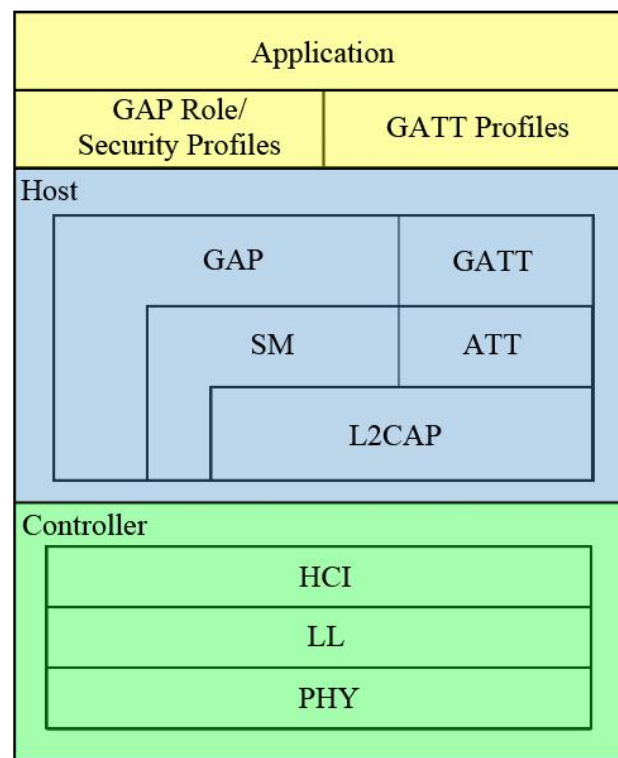


Figure 5 Protocol stack of Bluetooth Low Energy (modified [29])

The BLE protocol stack is built from the application layer, the host layer and the controller layer. The application layer hosts all the external Apps and profiles. The host layer consists of the Generic Access Profile (GAP), Generic Attribute Profile (GATT), Security Manager (SM), Attribute Protocol (ATT) and L2CAP. The GAP section is responsible for managing the device's access modes and procedures. In details, GAP administers device discovery, link establishment, applying security features, link termination, and device configuration. The GAP section is operating in one of four roles [29]: Broadcaster (advertiser), Observer (scanner), Peripheral (connectable advertiser/slave) and Central (connectable scanner/master). The GATT

section of the BLE protocol stack is designed to be used by the application for data communication between two connected devices. The connected devices can be either GATT client or GATT server. The GATT roles of client and server are independent from the BLE device being a slave or a master [29]. SM is responsible for device pairing and key distribution. BLE uses the AES-128 bit cryptography standard [28]. The ATT permits the attribute server to share certain data with the attribute client [28]. L2CAP component provides data services to upper layer protocols like security manager protocol and attribute protocol described earlier. It is responsible for data segmentation into smaller packets for the Link Layer (LL) and reassembly operation on the other end [29]. L2CAP is also in charge for adjusting the maximum number of transmission attempts allowed by a parameter called MaxTransmit [28] [29]. The L2CAP is a backend interface for the GAP that defines the generic procedures related to the discovery of BLE devices and link management aspects of connecting to other BLE devices [28]. On the controller layer, the HCI is used to allow reliable and easy communication between the Controller and the Host. There are many HCI transport layer standards depending on the application and hardware interface used. The most common ones are: Universal Serial Bus (USB) and Universal Asynchronous Receiver/Transmitter (UART) [29]. The link layer (LL) defines the packet structure. The key feature of the low-energy stack is a lightweight LL that provides ultra-low power idle mode operation, simple device discovery, and reliable point-to-multipoint data transfer with advanced power-save and encryption functionalities [28]. In BLE Link Layer, there is only one packet structure with two types of packets (advertising and data). See Figure 6.

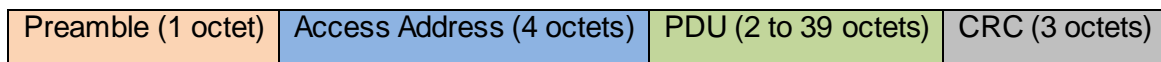


Figure 6 Link Layer packet format

The preamble can have two bit sequences “01010101” or “10101010” [28]. The Access Address is 32 bit long sequence and is used to inform the master in the pico-net which slave is requesting the connection to send data. Protocol Data Unit (PDU) contains the actual information that needs to be sent to the other BLE device. Then, a Cyclic Redundancy Check (CRC) algorithm is appended to the LL packet. The CRC is calculated over the payload (PDU) [28].

## 2.4.2 ZigBee IEEE 802.15.4

ZigBee was established in 2002 and it has been defined in the IEEE standard 802.15.4.2003 [30]. ZigBee IEEE 802.15.4 is a low power and low data rate wireless technology [31]. It includes mesh networking to the low power wireless space. Thus, it is suitable for many applications such as health care, home automation, input devices, remote controls...etc [32].

In 2012, two implementation specifications have been supported by ZigBee Alliance and they are ZigBee (Classic) and ZigBee PRO [32]. The ZigBee implementation option is designed to support networks that each can handle few hundreds of devices. The ZigBee PRO is a new feature set that is aimed at networks that each one can contain thousands of devices in it. ZigBee and ZigBee PRO feature sets are designed to interoperate with each other, ensuring long-term use and stability [32]. ZigBee channels are similar to BLE channels, since they have 2 MHz bandwidth, however, ZigBee channels have a 5 MHz spacing between each other [33].

ZigBee is built upon mesh, star or cluster-tree network topology [31]. If the topology is star, then there will be a simple master/slave configuration. In here, the master is called Personal Area Network (PAN) coordinator and it has to be a Full Function Device (FFD). On the other hand, the slaves can be Reduced Function Devices (RFD). However, if the network topology is mesh type, then multiple FFDs are used around the PAN coordinator to allow access for RFDs. Finally, if cluster-tree network topology is used, then a combination of both star and mesh topologies is used. Figure 7 shows these operating network topologies in clear manner.

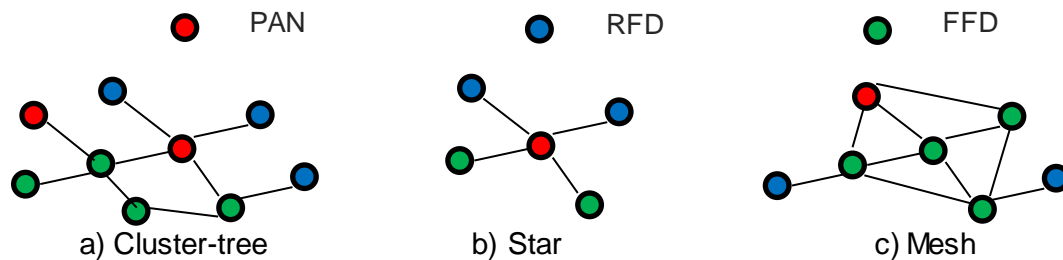


Figure 7 ZigBee Network topology types

IEEE 802.15.4.2003 standard offers two physical layer options based on the frequency band [30]. Both are based on Direct Sequence Spread Spectrum (DSSS). The data rate is 250 kbps at 2.4 GHz using Offset-Quadrature Phase Shift Keying (O-QPSK). Meanwhile, for other regional operating bands, the modulation technique used is Binary Phase Shift Keying (BPSK) [30] [31].

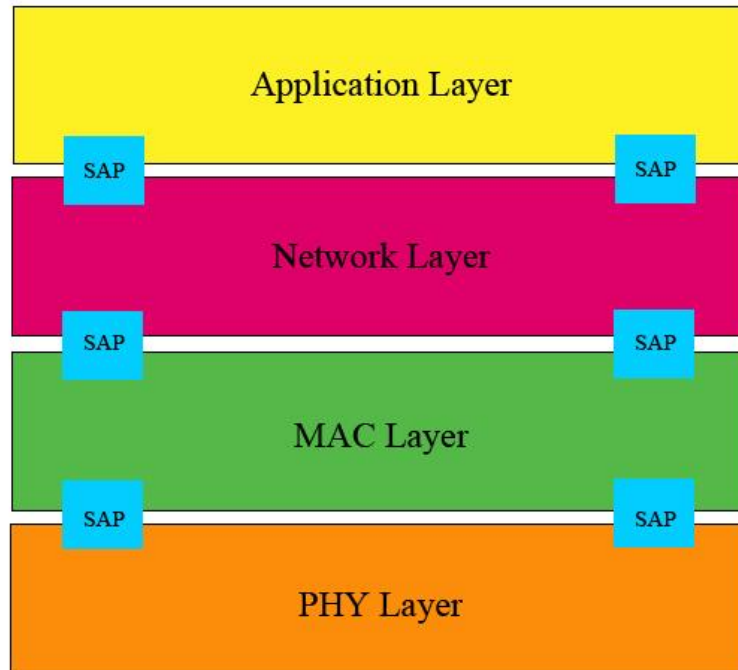


Figure 8 ZigBee stack architecture (modified [30])

The ZigBee stack architecture is shown in Figure 8. This stack is formed by four layers: the physical (PHY) layer, the MAC layer, the Network (NWK) layer and the application layer. Each layer in the stack performs tasks based on the commands it receives from the layer above it. These layers communicate between each other through the Service Access Points (SAPs) [30][31]. The PHY layer uses BPSK or O-QPSK modulation and demodulation to transmit and receive packets wirelessly. The MAC layer defines the network principles like network ID and beacon based network discovery. The NWK layer is responsible of ensuring good interworking with other devices as well as guaranteeing reliable packet transmission between devices [31]. This layer also adds security measures like encrypting the payload and checking joining devices. Finally, the application layer is responsible for running and hosting different applications.

### 2.4.3 Dash7 (ISO 18000-7)

Dash7 is a low power Radio Frequency IDentification (RFID) which is based on the ISO 18000-7 standard [34]. Dash7 is based on Interrogator and Tag network topology. Dash7 has two operational modes; mode 1 and mode 2. Dash7 mode1 applies BLAST concept in Wireless Sensor Network (WSN). BLAST stands for Bursty, Light, Asynchronous and Transitive. Therefore, the data transfer is carried in burst manner, the packet size is small, the connection between two devices is command-response oriented (i.e. no periodic hand-shaking is required), and supports changing networks. Dash7 mode 1 uses only one frequency channel centered on the 433.92 MHz ISM Band with a bandwidth of 500 kHz [35]. On the other side, Dash7 mode 2



has 8 configurable frequency channels of 216 kHz bandwidth [36]. Mode 2 is backward compatible and highly adopted in industry. Dash 7 mode 2 gives a peak data rate of 200 kbps, unlike in Dash 7 mode 1 where the peak data rate is only 100 kbps. Moreover, Dash 7 mode 2 implements a slotted or unslotted Carrier Sense Multiple Access (CSMA) at the MAC layer. This brings an improvement compared to Dash 7 mode 1, which is based on slotted ALOHA. The range of Dash7 can vary from 10 meters to 10 kilometers [36].

#### 2.4.4 Summary

After briefly discussing each applicable wireless technology, their related features and properties were summarized in Table 5.

No.	Technology	Frequency Band	Maximum Data Rate	Maximum Range	Modulation	Network Topology
1	Bluetooth V.1 Classic	2.4 GHz ISM	1 Mbps	150 m	GFSK	Star
2	Bluetooth V.2 + EDR	2.4 GHz ISM	3 Mbps	150 m	GFSK, $\pi/2$ -DPSK, 8-DPSK	
3	Bluetooth V.3 + HS	2.4 GHz ISM & 5 GHz	24 Mbps	10 m	GFSK, $\pi/2$ -DPSK, 8-DPSK	
4	Bluetooth Low Energy (BLE) V.4	2.4 GHz ISM	1 Mbps	100 m	GFSK	
5	ZigBee 802.15.4	868 MHz, 915 MHz, 2.4 GHz ISM	250 kbps	100 m	O-QPSK, BPSK	Star, Mesh, Cluster Tree
6	Dash7	433.04 - 434.79 MHz ISM	200 kbps	10m – 10km	FSK or GFSK	Peer-to-Peer (Interrogator and Tag)

Table 5 Properties of discussed wireless technologies

As mentioned in the system requirements (2.3), the communication system has to have low power consumption. Therefore, only BLE, ZigBee and Dash7 will be considered in the benchmarking chapter (3).

## 2.5 Applicable Collision Detection Sensors

### 2.5.1 Overview

This chapter is related to the investigation of most promising sensors which are applicable to measure the collision impacts on the player's body. Based on the system requirements section 2.3 , the head and the chest need to be monitored as the most devastating injuries are

developed from these areas. Moreover, the sensor should be cost efficient, small and able to measure impacts of 100g-Force or 100 Kg. Figure 9 shows the locations of the sensors.

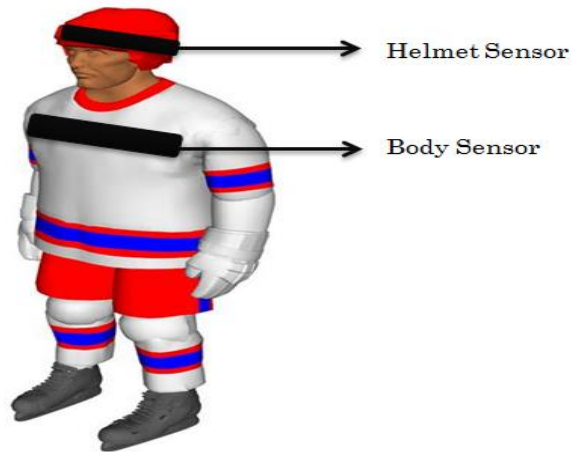


Figure 9 The sensors needed for the system.

### 2.5.2 Accelerometer

An accelerometer is a device that can measure acceleration forces. The measured forces are always in  $g$ -Force unit. Where, “ $g$ ” is the Earth’s gravity at sea level, which is equal to  $9.81 \text{ m/s}^2$  [37]. There are several types of accelerometers and they are different in construction principles: Piezoelectric, Piezoresistive and capacitive. However, they all follow the same working concept of displacing internal mass at the same rate as the packaging [37].

Accelerometers have a large sensing range from  $\text{mg}$  to  $\text{Mg}$  [38]. Also, Accelerometers require only a basic low pass filter (RC) interface circuit [39] [40].

### 2.5.3 Force Sensing Resistor (FSR)

FSR is a device that shows a decrease in its resistance when a force or pressure is applied on it. The resistance is very high when there is no force applied on it and low when the pressure is high (250 Ohm with 10 kg force) [41]. This can be seen in Figure 10.

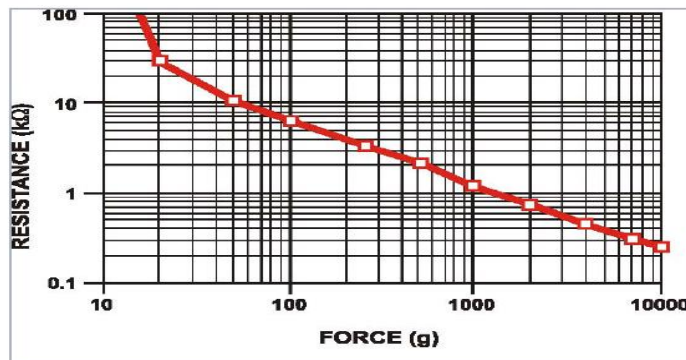


Figure 10 Resistance vs. Force [49]

This device is constructed from three layers as shown in Figure 11. The largest layer is called the base membrane. This layer has two sets of printed circuit pattern that are electrically distinct, with each set connecting to one trace on a tail. The other membrane is coated with FSR ink. When pressed, the FSR ink shorts the two traces together with a resistance that depends on an applied force. Finally, the middle layer is the air gap which is maintained by a spacer adhesive.

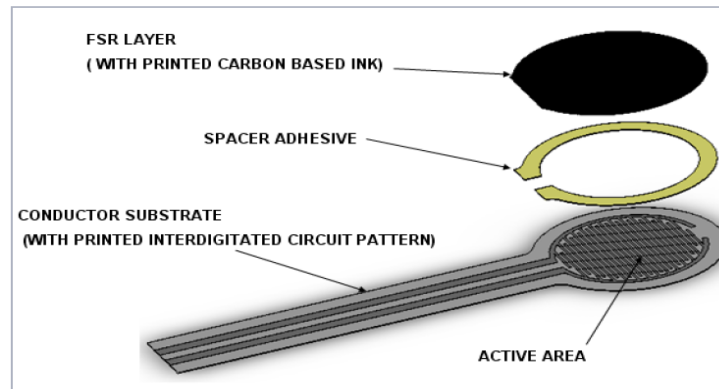


Figure 11 Basic FSR construction [49]

The force sensitive resistor sensor can be easily interfaced with a wireless transceiver since it has the basic voltage divider circuit layout [41].

#### 2.5.4 Load Cell

Load cell is a type of force sensors where it generates a very small potential difference when load is applied to it. Therefore, it requires a complex interface to do a specialized amplification on the electrical signal [42].

This force sensor contains a strain-gauge that changes its resistance when it experiences some deformation. Thus, allowing more or less electrical current depending on the type of deformation [42].

Load cell is able to handle high loads. However, it requires a complex electrical interface that is able to do specialized amplification and calibration [42]. It is also large in size compared to an accelerometer, or a force-sensitive resistor [38].

### 2.5.5 Summary and Comparison

After briefly discussing each applicable collision detection sensors, several commercial sensors were selected. Then, all these selected devices were listed in Table 6.

Sensor	Measure	Range	Interface	Component and Size	Price
Accelerometers	g-Force (g)	Large g-force sensing range from mg to Mg [38].	RC circuit [39] [40].	ADXL193 [39]: 5 mm x 5 mm x 2 mm. MMA1250 [40]: 10 mm x 8 mm x 3 mm.	For single-axis accelerometers with 200 to 250g, the price is between 3 to 13 USD [38]
Force Sensitive Resistor	Force/Mass (Kg)	Small force sensing range to 12 kg only	Voltage divider circuit [43]	FlexiForce A201-25 [44]: 203 mm x 10 mm x 0.2 mm.	10 to 30 USD [43]
Load Cell	Force (N)	Large force sensing range from mN to MN [38]	Low noise amplifier circuit [45]	LCR-250/N [45] : 19 mm x 19 mm x 13 mm.	For Load cells with 50 to 300Kg. the price is between 260 to 1925 USD. [38]

Table 6 Comparison between the discussed force sensors

From Table 6, it can be noticed that each sensor type has advantages and dis-advantages. These advantages and dis-advantages are summarized in Table 7.

Sensor	Advantages	Disadvantages
Accelerometers	Cheap, versatile, large range (mg to Mg) and small in size.	Data analysis is hard.
Force Sensitive Resistor	Simple, cheap and small in size.	Not suitable for precision measurements and small force sensing range to 12kg only.
Load Cell	large range (mN to MN)	Affected by temperature, expensive, complex interface and large in size.

Table 7 Advantages and disadvantages of the discussed sensing technologies

It can be noticed that the accelerometer is the most suitable sensor for the proposed system because it satisfies the system requirements of cost, size and ability to provide accurate data about the impact. Load cells are well suited for large force applications. However, they are usually large in size. Moreover, they are relatively expensive (260 to 1925 USD) when compared to accelerometers. Therefore, load cells cannot be used for the proposed application. Finally, FSR has a great price, small size, and an easy interface. Unfortunately, it has a maximum range of 12kg which is not suitable for this study.

Moreover, it is notable that the price of single-axis accelerometers is ranging between 3 to 13 USD for devices with sensitivity range of 200 to 250g [38]. From the datasheets [39] and [40] of the devices discussed in Table 6 and Table 7, it can be seen that the ADXL model has simpler architecture and smaller size when compared to MMA1250. However, MMA1250 is much cheaper, offers the same measurement range and has acceptable size. As a result, the accelerometer model to be used is MMA1250 because it is small (10mm×10mm×2mm), cheap (3 USD) and has high range (0 to 250g).

In the proposed system, each player will use 4 accelerometers; 3 for the head to give full information of the head impact and one for the chest area to determine the linear force applied to it. Since accelerometer MMA1250 model will be used, the total cost can be calculated as the following:

$$Sensors_{Price} = (4 \times 3 \times 20) = 240USD \quad (1)$$

### 3 Benchmarking the Applicable Wireless Technologies

In this section, each applicable wireless technology has been evaluated by nine measures taken from the proposed system requirements section (2.3). These measures are related to the network size, the expected cost of the system, the building components size, the required throughput, simultaneous monitoring capability, communication range, co-existence performance, power consumption and latency.

#### 3.1 Grading Methodology

The credibility of each technology in every benchmarking criterion is graded by a number from 3 to 0. Grade 3 indicates the best performer. Grade 2 is given to a technology with an acceptable performance. Grade 1 is given to technology with low performance. Finally, grade 0 is given to technology that fails in meeting the minimum requirement.

### 3.2 Network Size

Under the International Ice-Hockey Federation (IIHF) rules [46], each team may carry a maximum of 16 players and two goaltenders on their roster. On the other side, the National Hockey League (NHL) rules restrict the total number of players per game to 18, plus two goalkeepers [47]. As a result, it is safe to say that the maximum number of players in an Ice-Hockey game is 20 players per team. Therefore, the number of RF transceivers required to build the system should not be more than 21 (1 for the medical team and 20 for the players).

As discussed in section 2.4, the applicable wireless technologies for such application are BLE, ZigBee and Dash7. BLE uses pure star network topology and it has no multi-hop capability. As a result, the architecture of the system will be a piconet consisting of single master controlling several slaves. The master node will be the medical team station, while the player units will be slaves. Hence, the network size will be 21 devices. The second applicable wireless technology, ZigBee, can use different network topologies and multi-hop capability. However, these features do not help in reducing the number of required devices for this application, as all the players need to be monitored. Therefore, regardless of the network topology implemented, the network size will stay at 21 required devices. Finally, Dash7 uses peer-to-peer. The architecture of network is formed by a reader/interrogator and several tags. Since, there are 20 players to be monitored; the required network size is 21. Table 8 shows the network size requirement for the discussed wireless technologies.

Technology	BLE	ZigBee	Dash7
Pico-net size	21	21	21
Grade	3	3	3

Table 8 Network size for each wireless technology

### 3.3 Cost

The cost of the monitoring system should be low and feasible. This is important to allow teams to adopt this technology with minimal investment. As mentioned in the proposed system requirements 2.3, the cost of the system should not exceed 4700 USD. In addition, it has been found in previous section that the system can be formed by 21 transceiver modules; 20 for the players and 1 for the medical team station.

A BLE transceiver model TI CC2540 costs around 5 USD [38]. This specific module contains the protocol stack as well [48]. As calculated in equation (1), the price of the sensor units for all the 20 players is 240 USD. Therefore, the total cost of the system can be calculated as the following:

$$BLE\_System_{price} = (21 \times 5) + (4 \times 3 \times 20) = 345USD \quad (2)$$

In addition, the system can be formed by 21 ZigBee transceiver modules. Each module (TI CC2538) costs 8 USD [38]. This specific module contains the stack as well [49]. Therefore, the total cost of the system can be calculated as the following:

$$ZigBee\_System_{price} = (21 \times 8) + (4 \times 3 \times 20) = 408USD \quad (3)$$

The last option is Dash7. Dash7 requires 21 CC430 [50] MCUs (5 USD) and 21 small RF antennas (2 USD) [38]. Therefore, the total cost of the system can be calculated as the following:

$$Dash7\_System_{price} = (21 \times 5) + (21 \times 2) + (4 \times 3 \times 20) = 387USD \quad (4)$$

Thus, as a summary, the BLE based system offers the cheapest price with only 345 USD. Table 9 shows the total costs of the system depending on the telecommunication technology.

Technology	BLE (CC2540)	ZigBee (CC2538)	Dash7 (CC430)
Cost	\$345	\$408	\$387
Grade	3	1	2

Table 9 Cost of system depending on the telecommunication technology

### 3.4 Size

The size of each sensor and RF module located on the player must be small and light to allow the player to move freely. The accelerometer model to be used is MMA1250, and its dimensions were (10mm×10mm×2mm). The sizes of the most promising RF modules are listed in Table 10.

Technology	BLE (CC2540)	ZigBee (CC2538)	Dash7 (CC430)
Size	6mm x 6mm x 1mm	8mm x 8mm x 1mm	7.15mm x 7.15mm x 1mm
Grade	3	1	2

Table 10 Size of RF module chips

### 3.5 Throughput

As per the 2013 - 2014 NHL penalties statistics [51], the average number of penalty minutes per game is 11 minutes. Assuming that at every penalty minute two players get hit, the number of total transmitted bits can be calculated using equation (5).

$$Total\_Transmitted\_Bits = (22 \times 376) + (64 \times 22) = 9680bits$$

$$Throughput = \frac{Total\_Transmitted\_Bits}{Game\_Duration} = \frac{9680}{60min \times 60sec} = 2.689bps \quad (5)$$

The throughput needed is actually very low (nearly 3bps). Therefore, throughput is not a critical issue as all the following systems promise decent throughputs.

Technology	BLE	ZigBee	Dash7
Bit rate (Max)	1Mbps	250kbps	200kbps
Grade	3	2	1

Table 11 Bit rate of each wireless technology

### 3.6 Simultaneous Monitoring Capability

The number of active players in Ice-Hockey is 6, while the other 14 (NHL) or 12 (IIHF) are on the bench. However, all these players need to be equipped with safety monitoring system. BLE can handle up to 1000 devices [52]. ZigBee is designed to manage hundreds to thousands of devices [31]. Dash 7 is peer-to-peer technology. Therefore, it can communicate with one device at a time instance.

Technology	BLE	ZigBee	Dash7
Simultaneous connections	1000	100s to 1000s	1
Grade	2	3	1

Table 12 Simultaneous number of connections

### 3.7 Communication Range

In here, each applicable wireless technology has been investigated for its signal propagation range performance in an Ice-Hockey rink (see section 2.1). The link budget model used is the ITU model for indoor attenuation [53]. The basic model is expressed in equation 6.

$$L_{total(dB)} = 20\log_{10} f + N\log_{10} d + L_f(n) - 28 \quad (6)$$

Where,  $N$  is the distance power loss coefficient,  $f$  is the carrier frequency in MHz,  $d$  is the separation distance in meters between the medical station and the player,  $L_f$  is the floor penetration loss factor in dB and  $n$  is the number of floors between the medical station and the player.

Using equation 6, the link budget calculations for BLE, ZigBee and Dash7 were made and they can be seen below.

- Link Budget Calculation for BLE (2.4GHz ISM band)

$$L_{\min} = 20\log(2400) + 22\log(61) + [6 + 3(1-1)] - 28 = 84dB$$

$$L_{\max} = 20\log(2483.5) + 22\log(61) + [6 + 3(1-1)] - 28 = 85dB$$

$$P_{TX\_BLE} = 4dBm$$

$$P_{RX\_BLE\_L\min} = P_{TX\_BLE} + G_{TX} + G_{RX} - L_{\min} - FadeMargin = 4dBm + 0 + 0 - 84dB - 10dB$$

$$P_{RX\_BLE\_L\min} = -90dBm$$

$$P_{RX\_BLE\_L\max} = P_{TX\_BLE} + G_{TX} + G_{RX} - L_{\min} - FadeMargin = 4dBm + 0 + 0 - 85dB - 10dB$$

$$P_{RX\_BLE\_L\max} = -91dBm$$



- Link Budget Calculation for ZigBee (2.4GHz ISM band)

$$L_{\min} = 20\log(2405) + 22\log(61) + [6 + 3(1-1)] - 28 = 84.9dB$$

$$L_{\max} = 20\log(2480) + 22\log(61) + [6 + 3(1-1)] - 28 = 85.2dB$$

$$P_{TX\_ZigBee} = 20dBm$$

$$P_{RX\_ZigBee\_L\min} = P_{TX\_ZigBee} + G_{TX} + G_{RX} - L_{\min} - FadeMargin = 20dBm + 0 + 0 - 84.9dB - 10dB$$

$$P_{RX\_ZigBee\_L\min} = -74.9dBm$$

$$P_{RX\_ZigBee\_L\max} = P_{TX\_ZigBee} + G_{TX} + G_{RX} - L_{\min} - FadeMargin = 20dBm + 0 + 0 - 85.2dB - 10dB$$

$$P_{RX\_ZigBee\_L\max} = -75.2dBm$$

- Link Budget Calculation for Dash7 (433.04 to 434.79MHz Band)

$$L_{\min} = 20\log(433.04) + 22\log(61) + [6 + 3(1-1)] - 28 = 70dB$$

$$L_{\max} = 20\log(434.79) + 22\log(61) + [6 + 3(1-1)] - 28 = 70.04dB$$

$$P_{TX\_Dash7} = 15dBm$$

$$P_{RX\_Dash7\_L\min} = P_{TX\_Dash7} + G_{TX} + G_{RX} - L_{\min} - FadeMargin = 15dBm + 0 + 0 - 70dB - 10dB$$

$$P_{RX\_Dash7\_L\min} = -65dBm$$

$$P_{RX\_Dash7\_L\max} = P_{TX\_Dash7} + G_{TX} + G_{RX} - L_{\min} - FadeMargin = 15dBm + 0 + 0 - 70.04dB - 10dB$$

$$P_{RX\_Dash7\_L\max} = -65.04dBm$$

The above calculations can be summarized in a tabular form, as shown below.

Technology	Minimum Path Loss (dB)	Maximum Path Loss (dB)	P <sub>TX</sub> (dBm)	Minimum P <sub>RX</sub> (dBm)	Maximum P <sub>RX</sub> (dBm)	Receiver Sensitivity (dBm)	Difference Ratio (dB)	Grade
BLE (TI CC2540)	84	85	4	-91	-90	-93	2 to 3	1
ZigBee (TI CC2538)	84.9	85.2	20	-75.2	-74.9	-97	21.8 to 22.1	2
Dash7 (TI CC430)	70	70.04	15	-65.04	-65	-96	30.96 to 31	3

Table 13 link budget calculation summary table

### 3.8 Coexistence Performance

The system chosen should be able to send data in busy environment and/or be able to mitigate interference from systems co-existing in the same spectrum. BLE uses frequency hopping to reduce the effect of interference. It also offers 9 data channels and 3 advertising channels when there are three Wi-Fi channels occupied. ZigBee uses Direct Sequence Spread Spectrum (DSSS) to reduce the effect of interference. It offers only 4 communication channels

when three Wi-Fi networks exist. The channel availability for BLE and ZigBee can be seen in Figure 12 and Figure 13.

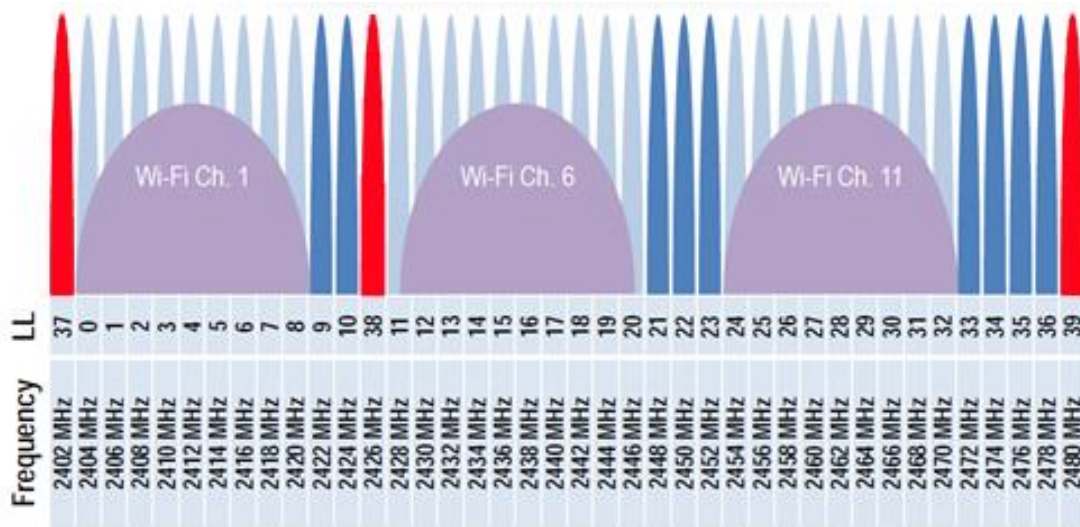


Figure 12 BLE channels coexisting with Wi-Fi (modified [33])

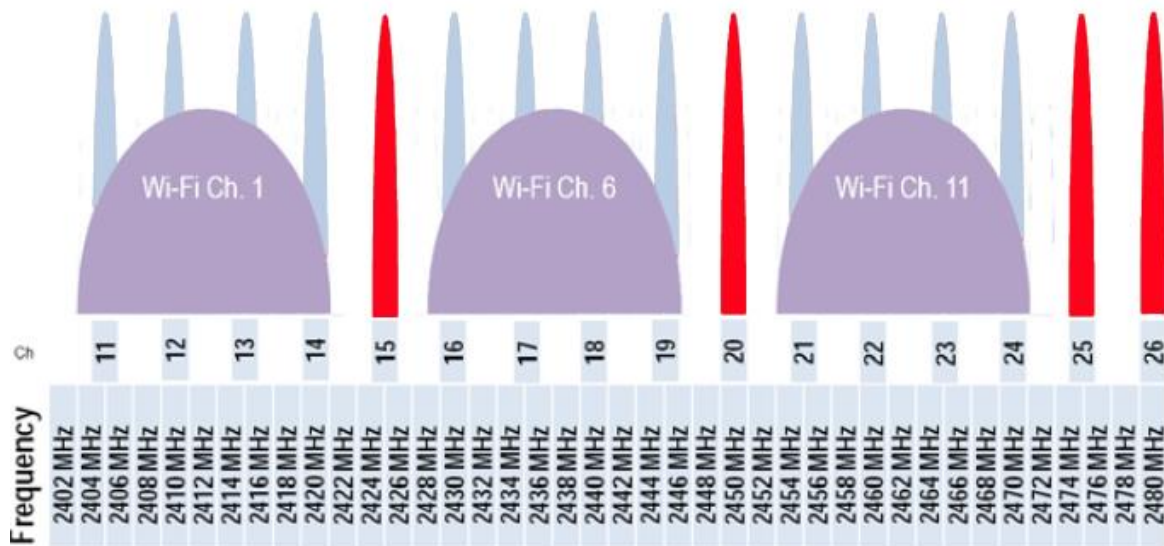


Figure 13 ZigBee channels coexisting with Wi-Fi (modified [33])

On the other hand, Dash7 and Wi-Fi are not in the same spectrum. Hence, they do not interfere with each other. Table 14 summarizes the coexistence performance of BLE, ZigBee and Dash7 with Wi-Fi.

Technology	BLE	ZigBee	Dash7
Coexistence Performance	9 data channels and 3 advertising channels are available.	4 channels are available.	Not in the same spectrum.
Result	2	1	3

Table 14 Coexistence Performance comparison

### 3.9 Power Consumption

From the Dash7 white paper [34], the average powers for Dash7, BLE and ZigBee have been studied. The scenario was to send ten 256-byte messages per day and then calculate the average power. BLE has an average power of 50uW. This translates into 20480 transmitted bits. The average power consumption per bit is 20480 divided by 50uW, which is  $2.44 \times 10^{-9}$  W/bit. On the other hand, ZigBee has much higher average power (414uW). This yields into  $2.02 \times 10^{-8}$  W/bit. Finally, Dash7 has the lowest average power consumption with 42uW. Therefore, the power per bit is equal to  $2.051 \times 10^{-9}$  W/bit.

Technology	BLE	ZigBee	Dash7
Power consumption	$2.44 \times 10^{-9}$ W/bit	$2.02 \times 10^{-8}$ W/bit	$2.051 \times 10^{-9}$ W/bit
Result	2	1	3

Table 15 Power consumption comparison

### 3.10 Latency

As mentioned in the system requirements section 2.3, the latency or the average packet delay is an important measure for this application as the medical team has to be informed very quickly about the impacted players. From sources [32], [33] and [54], Table 16 has been formed.

Technology	BLE	ZigBee	Dash7
Average Packet Delay	2.5ms [33]	20ms [32]	100ms to 2s [54]
Result	3	2	1

Table 16 Average Packet Delay

### 3.11 Summary and Overall Performance

After benchmarking the applicable wireless technologies, their related features and properties were summarized in Table 17. Consequently, the grading made was added to find the best technology (see Table 18).

Technology	BLE	ZigBee	Dash7
Cost	\$345	\$408	\$387
Size	6mm x 6mm x 1mm	8mm x 8mm x 1mm	7.15mm x 7.15mm x 1mm
Throughput	1Mbps	250kbps	200kbps
Network Size	21	21	21
Simultaneous Monitoring Capability	1000	100s to 1000s	1
Range	Slightly more than 61 meters	Much more than 61meters	Much more than 61 meters
Coexistence Performance	9 data channels and 3 advertising channels are available.	4 channels are available.	Not in the same spectrum.
Power consumption	2.44x10 <sup>-9</sup> W/bit	2.02x10 <sup>-8</sup> W/bit	2.051x10 <sup>-9</sup> W/bit
Latency	2.5 ms	20 ms	100 ms

Table 17 Benchmarking summary table

Technology	BLE	ZigBee	Dash7
Cost	3	1	2
Size	3	1	2
Throughput	3	2	1
Network Size	3	3	3
Simultaneous Monitoring Capability	2	3	1
Range	1	2	3
Coexistence Performance	2	1	3
Power Consumption	2	1	3
Latency	3	2	1
Grade	22/27	16/27	19/27

Table 18 Overall Performance table

From the above tables (Table 17 and Table 18), it can be seen that the BLE technology is the most suitable for the proposed application. Moreover, Bluetooth technology is highly adopted in industry and it proven to be reliable. Therefore, it is more likely that BLE will be used in many devices in the future (e.g., in laptops, smart phones, health products, etc.). This will decrease the price of this application further as then the medical team can monitor the players from a smart phone for example.

## **4 Evaluation of the Proposed System**

The former sections present the background on sport safety monitoring systems, the literature review on relevant existing systems, the proposed system requirements and the benchmarking of applicable sensors and wireless technologies.

In this section, the most suitable wireless technology for the proposed application will be evaluated. Firstly, the proposed system construction will be described. Then, the channel model will be studied. This is required to empower accurate system evaluation. Lastly, the figures of merit for quality of the proposed system are inspected.

### **4.1 Proposed System Architecture**

From section 2.5 and chapter 3, the proposed system architecture will be based on Accelerometers and BLE transceivers. In each player unit, there will be four accelerometers, where, three of them will be for the head, and one for the body. Also, it will contain a BLE transceiver to transmit data from sensors to the medical team monitoring station. The medical team monitoring station will have a single BLE transceiver which will receive data from the players units and then responding with relevant polling packets.

### **4.2 Channel Model**

Based on the scenario described in section 2.1, it is noticeable that the values of the coherence time,  $T_C$ , and coherence bandwidth,  $B_C$ , are important to select the proper channel model. These parameters indicate the changeability in channel characteristics with time and frequency.

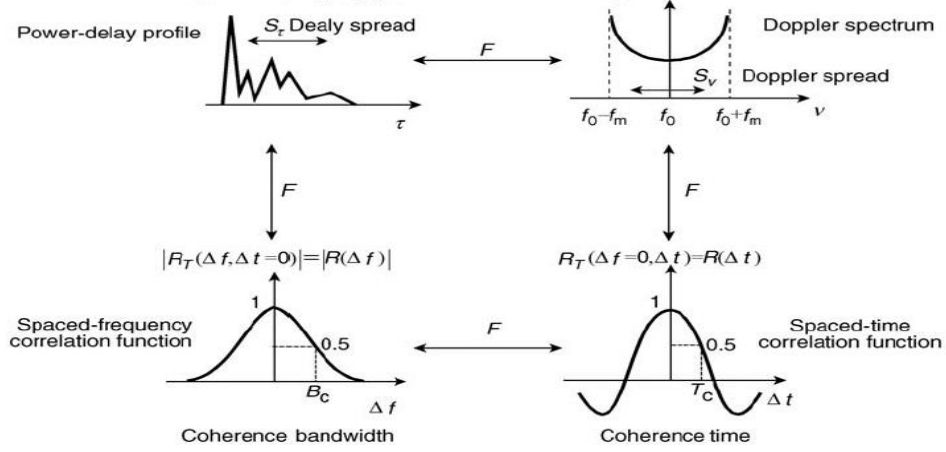


Figure 14 Simplified channel characterization functions and parameters [55]

As shown in Figure 14, the coherence bandwidth,  $B_C$ , and RMS delay spread,  $\sigma_\tau$ , are used to determine if the channel fading is flat or frequency selective. On the other hand, the coherence time,  $T_C$ , and Doppler spread,  $B_S$ , are used to define if the channel is experiencing a fast or slow fading [56].

In order to get the value of  $\sigma_\tau$ , several papers investigating the channel behavior for 2.4 GHz RF signals propagation in indoor environments were researched. The most relevant paper was written by Kemp and Bryant [57] because it studies the channel behavior in areas with dimensions similar to the ice hockey rink ones. This paper measures the 2.4 GHz RF signals propagation in different industrial environments. The measurements are conducted in six types of sites, and the results are shown in Table 19.

Site	Mean RMS Delay Spread (ns)
Petrochemical plant	38
Transformer station	85
Manufacturing plant	44
Car park amongst multistory buildings	74
Mine in granite	16
Coal Mine	23

Table 19 Mean RMS Delay Spread measurements for different industrial sites [57]

Taking the largest mean RMS delay spread which is 85ns, the coherence bandwidth ( $B_{C,50\%}$ ) with 50% correlation can be approximated by equation 7 [56].

$$B_{C,50\%} = \frac{1}{5\sigma_\tau} = \frac{1}{5 \times 85ns} = 2.353MHz \quad (7)$$

It can be concluded that the determined 50% coherence bandwidth is larger than the bandwidth of the signal which is 2 MHz (single BLE channel bandwidth). Consequently, the

fading is flat. Hence, the signal will see the channel constant. After that, the channel is examined if it experiences fast fading or slow fading. This can be achieved by using the values of  $T_C$  and  $B_S$ . The 50% coherence time,  $T_{C,50\%}$ , can be calculated using the equation 8 [56]:

$$T_{C,50\%} = \frac{9}{16\pi f_d} = \frac{1}{16 \times \pi \times \left( f_c \frac{v}{c} \right)} \quad (8)$$

$$T_{C,50\%} = \frac{1}{16 \times \pi \times \left( 2\text{MHz} \frac{8.89\text{m/s}}{3 \times 10^8 \text{m/s}} \right)} = 0.3356755\text{sec}$$

Where  $f_d$  is the maximum Doppler frequency,  $f_c$  is the carrier frequency,  $v$  is the maximum velocity of player [58], and  $c$  is the speed of light.

It can be noticed that  $T_{C,50\%}$  is larger than symbol duration,  $T_s$  which is  $1\mu\text{s}$  ( $1/1\text{Mbps}$ ). Hence, the communication channel is flat and slowly faded, and looks like Figure 15.

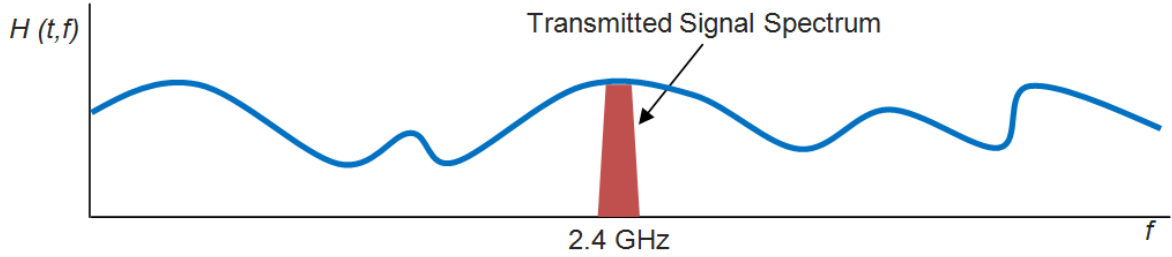


Figure 15 Transmitted signal in slowly faded channel

### 4.3 Bit Error Rate (BER) of BLE

Bit Error Rate (BER) is an important performance measure in wireless communication. BER is the ratio between the number of erroneous transmitted bits and the total number of transmitted bits during a certain duration. BER can be estimated by the use of bit error probability,  $P_b$ .  $P_b$  expression is derived from the modulation/demodulation scheme used and the relevant channel model.

The modulation used in BLE is GFSK with BT equal to 0.5 and selectable modulation index,  $h$ , from 0.45 to 0.55 [28]. When  $h$  of the GFSK is set to 0.5, the modulation becomes Gaussian Minimum Shift Keying (GMSK). GMSK is an MSK modem with Gaussian low pass filter used to shape the incoming bipolar bits (+1s and -1s). A modulation index,  $h$ , of 0.5 ( $1/2T_s$ ) corresponds to the minimum frequency spacing that allows two FSK signals to be coherently orthogonal [59]. The probability of error of MSK is the same as the BPSK when the observation time is  $2T_s$ . This is because the minimum distance,  $d_{min}$ , becomes the same for both modulations. This can be seen clearly in Figure 16.

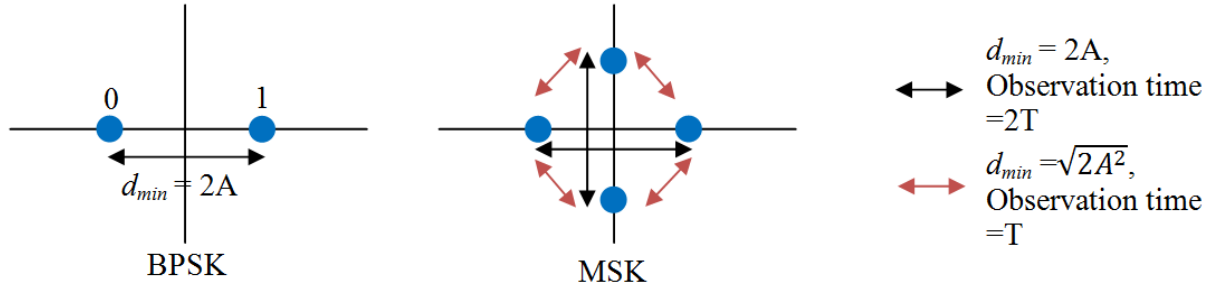


Figure 16 Constellation of BPSK and MSK

The bit error probabilities of BPSK in AWGN, slow flat Rayleigh and slow flat Rician channels are expressed in equations 9, 10 and 11 [59] [60].

$$P_{MSK\_2T\_AWGN} = P_{BPSK\_AWGN} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) = Q(\sqrt{2\gamma}) = \frac{1}{2} \operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (9)$$

$$P_{MSK\_2T\_Slow\&Flat\_fading\_Rayleigh} = P_{BPSK\_Slow\&Flat\_fading\_Rayleigh} = \frac{1}{2} \left(1 - \sqrt{\frac{\Gamma}{1+\Gamma}}\right) \quad (10)$$

$$P_{MSK\_2T\_SlowFlat\_fading\_Rician} = P_{BPSK\_Slow\&Flat\_fading\_Rician} = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \frac{(K+1)\sin^2 \theta}{(K+1)\sin^2 \theta + \Gamma} \exp\left(-\frac{K\Gamma}{(K+1)\sin^2 \theta + \Gamma}\right) d\theta \quad (11)$$

The parameter  $\Gamma$ , is the average  $E_b/N_0$  of the fading channel and it is equivalent to the expectation of  $E_b/N_0$  ( $\gamma$ ). This is shown in equation 12.

$$\Gamma = Ex[\gamma] = Ex[fading\_channel\_Random\_Variable] \frac{E_b}{N_0} \quad (12)$$

GMSK performance is dependent on the Bandwidth-Time product, BT, parameter. As BT decreases, the more signals will get cramped together, hence introducing inter-symbol-interference (ISI). The relationship between the degradation from ISI and BT is shown in Figure 17.



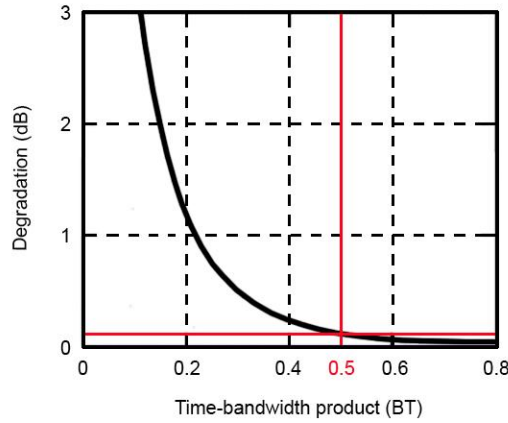


Figure 17 Theoretical Eb/No degradation of GMSK for varying BT (modified [59])

Also, the relationship between the  $E_b/N_0$  degradation and Gaussian filter degradation factor of certain  $BT$ ,  $\alpha$ , is described by the following equation [59].

$$Degradation(dB) = 10 \log_{10} \left( \frac{\alpha}{2} \right) \quad (13)$$

Now, in order to get  $\alpha$ , the degradation should be extracted from Figure 14. Since  $BT$  is set to 0.5. Therefore, the degradation is approximately -0.125 dB. Then, equation 13 was reorganized to solve for  $\alpha$ .

$$\begin{aligned} \alpha &= 10^{\left( \frac{Degradation(dB)}{10} \right)} \times 2 \\ \alpha &= 10^{\left( \frac{-0.125dB}{10} \right)} \times 2 \\ \alpha &= 10^{\left( \frac{-0.125dB}{10} \right)} \times 2 = 1.943256 \end{aligned}$$

As a result, the performance of GMSK in AWGN channel can be expressed as equation 14 [59].

$$P_{GMSK\_2T\_AWGN} = Q \left( \sqrt{\frac{\alpha E_b}{N_0}} \right) = Q(\sqrt{\alpha \gamma}) = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{\alpha E_b}{2 N_0}} \right) \quad (14)$$

Now, in order to derive the bit error probabilities of the coherent GMSK with 2T observation time in fading channels, the AWGN GMSK probability of error,  $P_{GMSK\_AWGN}$ , should be integrated with the fading channel distribution,  $f_{\gamma}(\gamma)$ . This will be expressed as equation 15.

$$P_{GMSK\_Fading} = \int_0^{\infty} P_{GMSK\_AWGN} f_{\gamma}(\gamma) d\gamma = \int_0^{\infty} Q(\sqrt{\alpha \gamma}) f_{\gamma}(\gamma) d\gamma \quad (15)$$

Where,  $Q(x)$  is the probability that a Gaussian random variable will obtain a value larger than  $x$  standard deviations above the mean [61]. This can be written by Craig alternative expression [61] shown in equation 16:

$$Q(x) = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \exp\left(-\frac{x^2}{2\sin^2 \theta}\right) d\theta \quad (16)$$

Therefore,  $Q(\sqrt{\alpha\gamma})$  can be expressed as the following

$$Q(\sqrt{\alpha\gamma}) = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \exp\left(-\frac{(\sqrt{\alpha\gamma})^2}{2\sin^2 \theta}\right) d\theta = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \exp\left(-\frac{\alpha\gamma}{2\sin^2 \theta}\right) d\theta \quad (17)$$

Also, the moment generating function MGF is defined by equation 18 [60].

$$M_X(s) = E[e^{sx}] = \int_{-\infty}^{\infty} e^{sx} f_X(x) dx \quad (18)$$

Using equation 18, the MGFs of Rayleigh and Rician channels are presented in equations 19 and 20.

$$M_{\gamma\_Rayleigh}(s) = \int_{-\infty}^{\infty} e^{s\gamma} f_{\gamma\_Rayleigh}(\gamma) d\gamma = \frac{1}{1-\Gamma s} \quad (19)$$

$$M_{\gamma\_Rician}(s) = \int_{-\infty}^{\infty} e^{s\gamma} f_{\gamma\_Rician}(\gamma) d\gamma = \frac{K+1}{K+1-\Gamma s} \exp\left(\frac{K\Gamma s}{K+1-\Gamma s}\right) \quad (20)$$

Where, the probability density functions of Rayleigh  $f_{\gamma\_Rayleigh}(\gamma)$  and Rician  $f_{\gamma\_Rician}(\gamma)$  channels are presented in equations (21) and (22) [60].

$$f_{\gamma\_Rayleigh}(\gamma) = \frac{1}{\Gamma} \exp\left(-\frac{\gamma}{\Gamma}\right) \quad (21)$$

$$f_{\gamma\_Rician}(\gamma) = \frac{(1+K)e^{-K}}{\Gamma} \exp\left(-\frac{(1+K)\gamma}{\Gamma}\right) I_0\left(\frac{4K(1+K)\gamma}{\Gamma}\right) \quad (22)$$

Using Craig's Q-function expression and MGFs of Rayleigh and Rician fading channels, the fading bit error probability can be reduced to equation (23).

$$P_{GMSK\_Fading} = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} M_{\gamma} \left( -\frac{1}{\frac{2}{\alpha} \sin^2 \theta} \right) d\theta \quad (23)$$

Substituting (19) and (20) into equation (23), yields

$$P_{GMSK\_2T\_Slow\&Flat\_fading\_Rayleigh} = \frac{1}{2} \left( 1 - \sqrt{\frac{\frac{\alpha}{2}\Gamma}{1 + \frac{\alpha}{2}\Gamma}} \right) \quad (24)$$

$$P_{GMSK\_2T\_Slow\&Flat\_fading\_Rician} = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \frac{(K+1)\frac{2}{\alpha} \sin^2 \theta}{(K+1)\frac{2}{\alpha} \sin^2 \theta + \Gamma} \exp\left(-\frac{K\Gamma}{(K+1)\frac{2}{\alpha} \sin^2 \theta + \Gamma}\right) d\theta \quad (25)$$

In addition, in BLE, Frequency hopping is employed with GFSK or GMSK. In FHSS, when two users transmit simultaneously in the same frequency band, a collision occurs. Consequently, the sent bit will be corrupted. The error probability of the collided band should be 0.5 [62]. The bit error probabilities of Slow Frequency Hopping (SFH) GMSK in AWGN and slow flat Rayleigh and Rician fading channels are presented in equations (26), (27) and (28).

$$P_{SFH-GMSK\_AWGN} = P_{GMSK\_AWGN} \times P_{no\_collision} + \frac{1}{2} \times P_{collision} \quad (26)$$

$$P_{SFH-GMSK\_Slow\&Flat\_Rayleigh\_fading} = P_{GMSK\_Slow\&Flat\_Rayleigh\_fading} \times P_{no\_collision} + \frac{1}{2} \times P_{collision} \quad (27)$$

$$P_{SFH-GMSK\_Slow\&Flat\_Rician\_fading} = P_{GMSK\_Slow\&Flat\_Rician\_fading} \times P_{no\_collision} + \frac{1}{2} \times P_{collision} \quad (28)$$

Where,  $P_{collision}$  is the probability of collision between transmitting users and  $P_{no\_collision}$  is the probability of no collision between users. These probabilities can be expressed as:

$$P_{no\_collision} = \left(1 - \frac{1}{M}\right)^{K-1} \quad (29)$$

$$P_{collision} = 1 - \left(1 - \frac{1}{M}\right)^{K-1} \quad (30)$$

Where,  $M$  is the number of frequency channels and  $K-1$  is the number of interfering users.

#### 4.4 Packet Error Rate (PER) of BLE

After finding the BERs of SFH-GMSK in AWGN, slow flat Rayleigh and slow flat Rician channels with different scenarios; one interfering user and no interfering users, the respective packet error rates should be calculated to give better insight of the system performance. The packet error rate, or PER, is the number of erroneously received packets divided by the total number of received packets. Of course, the receiver will mark a packet corrupted, if one or more bits are incorrect. PER can be calculated from the BER and the number of bits inside a packet,  $N_{bits}$ , using equation 31 [63].

$$PER = 1 - (1 - BER)^{N_{bits}} \quad (31)$$

#### 4.5 Gilbert-Elliot Model

Gilbert-Elliot model is used for describing the bursty errors behavior in wireless channels [64]. The Gilbert-Elliot model is a hidden Markov chain, which is a stochastic process with a countable state space [64]. The Markov chain resides in one of the states at each time instance,

and the probability of going to another state is a function of the present state [64]. The simplest Gilbert-Elliot model is formed by a two-state hidden Markov chain, in which the two states are denoted as “Good” and “Bad” (see Figure 18). The “Good” state means that no packet error occurs. On the other side, the “Bad” state indicates that some packet errors exist.

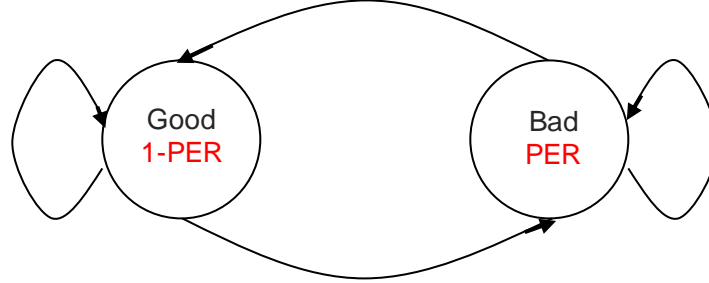


Figure 18 Two-state Gilbert-Elliot Model

Therefore, it can be seen that the distribution of transmission attempts and packet delay is geometrically distributed, as the packet will fail for a while, then it will pass. The geometric distribution has the following basic properties [65]:

$$\Pr(X = k) = (1 - p)^{k-1} p = q^{k-1} p$$

$$E(X) = \frac{1}{p}$$

$$\text{var}(X) = \frac{1-p}{p^2} = \frac{q}{p^2}$$

Where,  $p$  is the probability of success,  $q$  is the probability of failure and  $k$  is the number of trial.

## 4.6 Average Number of Transmission Attempts

### 4.6.1 MaxTransmit

In BLE, the number of transmission attempts can be controlled by specifying the MaxTransmit parameter in L2CAP (see section 2.4.1). The value can be no retransmissions, 1 to 255 retransmissions or infinite retransmissions. This parameter is 1 octet long. This field controls the number of retransmissions that L2CAP is allowed to try in retransmission mode and enhanced retransmission mode before accepting that a packet and the channel are lost. When a packet is lost after being transmitted MaxTransmit times the channel shall be disconnected by sending a disconnect request. The minimum value is 1 (one transmission is permitted). [28]

### 4.6.2 MaxTransmit is set to Infinite

When the MaxTransmit parameter is set to zero (00000000), then the number of transmissions is infinite. To find the average number of transmission attempts from a single

player unit to the medical team station, the geometric distribution equations (32) and (33) were used.

$$\Pr\{Tx = n\} = PER^{n-1} (1 - PER) \quad (32)$$

$$E\{Tx\} = \frac{1}{(1 - PER)} \quad (33)$$

#### 4.6.3 MaxTransmit is set to 256

When the MaxTransmit parameter is set between 2 to 256 (00000010 to 11111111), then the number of retransmissions is from 1 to 255. In order to get the expectation of the required number of transmissions to deliver a correct packet in this limited attempts case, a truncated probability should be used. This probability takes the original Probability Density Function (PDF) and restrict it between two limits  $a$  and  $b$ . The restriction is made by dividing the PDF,  $f(x)$ , over a parameter beta,  $\beta$ .  $\beta$  is the subtraction between the higher limit Cumulative Distribution Function (CDF),  $F(b)$ , and lower limit CDF,  $F(a)$  [66] [67]. Also, it should be mentioned that the CDF is the integral of the PDF. Thus, the sum of the truncated probability will be 1. The truncated probability used in this study is expressed in equation (34).

$$\begin{aligned} Truncated\_Pr = f(x|a < X \leq b) &= \frac{g(x)}{\beta} = \frac{g(x)}{F(b) - F(a)} = \frac{p(1-p)^{x-1}}{(1-p)^a - (1-p)^b} \\ Truncated\_Pr = f(x|a < X \leq b) &= \frac{p(1-p)^{x-1}}{(1-p)^a - (1-p)^b} = \frac{(1-PER)(PER)^{255}}{(PER)^1 - (PER)^{256}} \end{aligned} \quad (34)$$

The average packet transmissions needed is described in equation (35).

$$\begin{aligned} E[Tx\_truncated] &= \frac{\int_a^b xg(x)dx}{F(b) - F(a)} = \frac{\int_a^b xp(1-p)^{x-1}dx}{(1-p)^a - (1-p)^b} = \frac{\int_1^{256} xp(1-p)^{x-1}dx}{(1-p)^1 - (1-p)^{256}} \\ E[Tx\_truncated] &= \frac{\int_1^{256} Tx(1-PER)(PER)^{tx-1}dx}{(PER)^1 - (PER)^{256}} \end{aligned} \quad (35)$$

## 4.7 Average Packet Delay

### 4.7.1 MaxTransmit is set to Infinite

When the MaxTransmit parameter is set to zero '00000000', then the number of transmissions is infinite. To find the average packet delay from a single player unit to the medical team station, the following geometric distribution equations were used.

$$\Pr\{Tx = n\} = PER^{n-1} (1 - PER) \quad (36)$$

$$E\{Tx\} = \frac{1}{(1 - PER)} \quad (37)$$

Now, to get the total packet delay, the average packet delay should be added to the time of packet being acknowledged by the receiver. Therefore, the equation for total packet delay can be expressed as shown in equation (38).

$$Total\_Packet\_Delay = Data\_Packet\_Delay + Polling\_Packet\_Delay \quad (38)$$

#### 4.7.2 MaxTransmit is set to 256

Similar to the steps in section 4.6.3, a truncated probability is needed to represent the packet delay when MaxTransmit parameter is set to 256. This truncated probability is expressed in equation (39).

$$Truncated\_Pr = f(x|a < X \leq b) = \frac{g(x)}{F(b) - F(a)} = \frac{p(1-p)^{x-1}}{(1-p)^a - (1-p)^b} \quad (39)$$

$$Truncated\_Pr = f(x|a < X \leq b) = \frac{p(1-p)^{x-1}}{(1-p^a) - (1-p^b)} = \frac{(1-PER)(PER)^{255}}{(PER)^1 - (PER)^{256}}$$

The average packet delay is described in equation (40).

$$E[Delay\_truncated] = \frac{\int_a^b xg(x)dx}{F(b) - F(a)} = \frac{\int_a^b xp(1-p)^{x-1}dx}{(1-p)^a - (1-p)^b} = \frac{\int_1^{256} xp(1-p)^{x-1}dx}{(1-p)^1 - (1-p)^{256}} \quad (40)$$

$$E[Delay\_truncated] = \frac{\int_1^{256} Tx(1-PER)(PER)^{Tx-1}dx}{(PER)^1 - (PER)^{256}}$$

Now, to get the total packet delay, equation (38) should be used.

#### 4.8 Packet Loss of BLE (MaxTransmit = 256)

The final figure of merit for system quality in this Master Thesis is related to the packet loss percentage occurring at different studied cases. Packet loss is a quality parameter that indicates the number or rate of transmitted packets not reaching the receiver. The packet loss percentage can be calculated by equation (41).

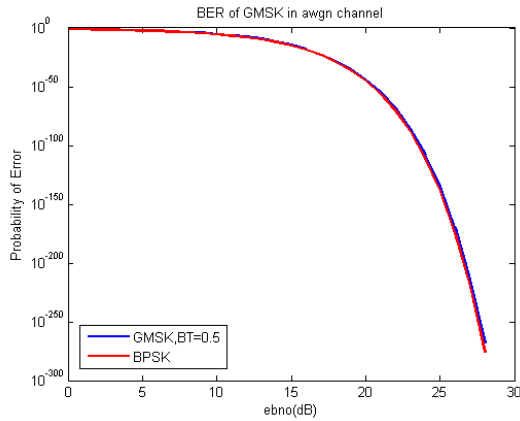
$$Packet\_Loss\_Percentage = \frac{Data\_Packets - Polling\_Packets}{Data\_Packets} \quad (41)$$

## 5 System Results and Analysis

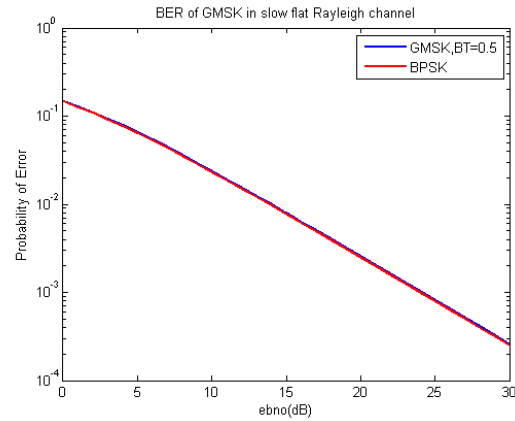
In this section, all the results generated using the equations in Chapter 4 will be presented. Add to that, these graphs will be interpreted to evaluate the performance of the actual application.

### 5.1 BER Results

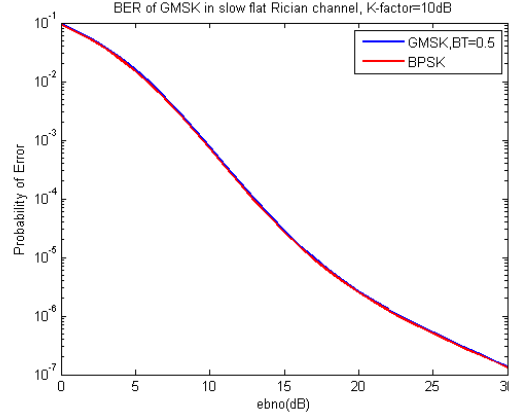
The BER graphs presented in Figure 19 shows the performance of a GMSK modem with  $BT=0.5$  in AWGN channel, slow and flat Rayleigh fading channel and slow and flat Rician fading channel with K-factor=10dB. These BER graphs are developed from equations 9, 10, 11, 14, 24 and 25. The BERs of GMSK is slightly more than the ones of BPSK or MSK with 2T integration period. This is expected because a Gaussian filter with smaller BT entails more bits to be restricted in smaller bandwidth. Therefore, the effect of Inter-symbol Interference (ISI) becomes more apparent. Also, as expected, the performance of the system is at its best when the channel is AWGN, while the performance of the system is at its worst when the channel is Rayleigh. This is caused because AWGN is a pure Line-Of-Sight (LOS) channel with additive interference on all frequencies. On the other hand, Rayleigh fading channel is purely Non-Line-Of-Sight (NLOS). Rician fading channel inherits both characteristics of AWGN and Rayleigh channels depending on the K-factor value, which is the ratio between the specular signal energy to the scattered signal energy.



(a) AWGN



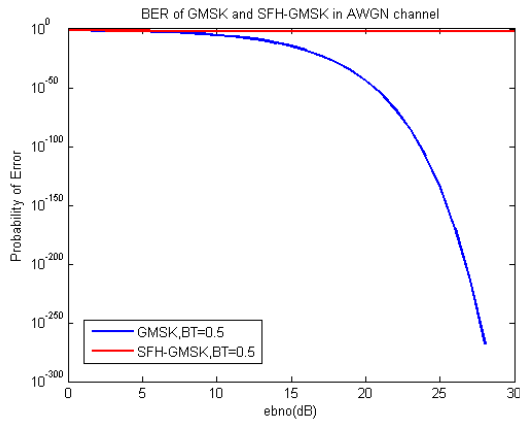
(b) Rayleigh



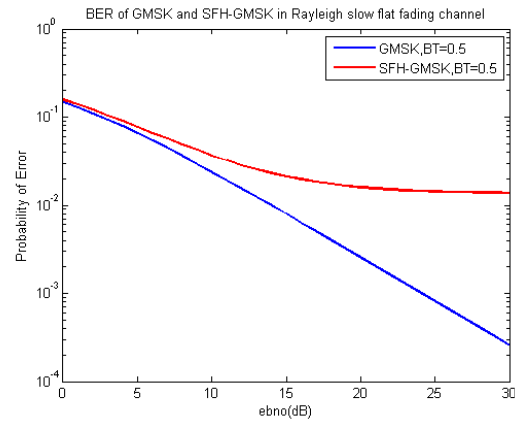
(c) Rician, K-factor=10dB

Figure 19 BER of GMSK in (a) AWGN, (b) Slow & Flat Rayleigh and (c) Slow & Flat Rician with K-factor=10dB

Moreover, BLE uses frequency hopping with GMSK. The bit error probabilities of Slow Frequency Hopping (SFH) GMSK in AWGN, slow flat Rayleigh fading and slow flat Rician fading channels are expressed in equations 26, 27 and 28. These equations produce Figure 20 a, b and c. These BER graphs illustrate the performance of SFH-GMSK with BT=0.5 when there is one interfering user and when there are no interfering users. It can be seen that when there are no interfering users the SFH-GMSK acts as a normal GMSK. On the other hand, when there is one interfering user, the BER becomes higher and has a lower bound equal to  $\frac{1}{2} \times P_{collision}$ .

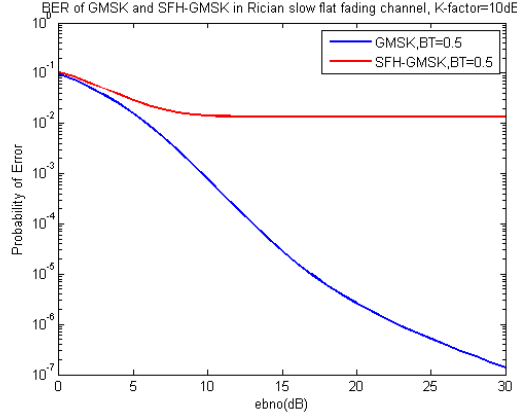


(a) AWGN



(b) Rayleigh



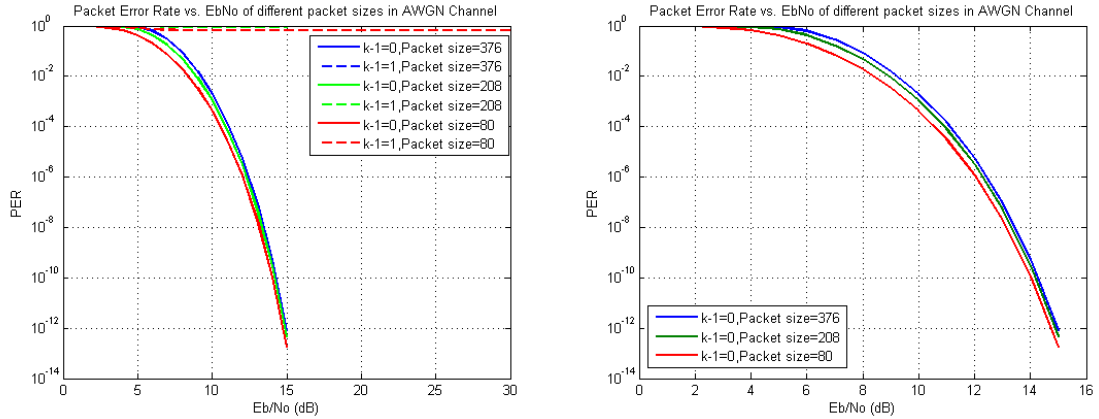


(c) Rician, K-factor=10dB

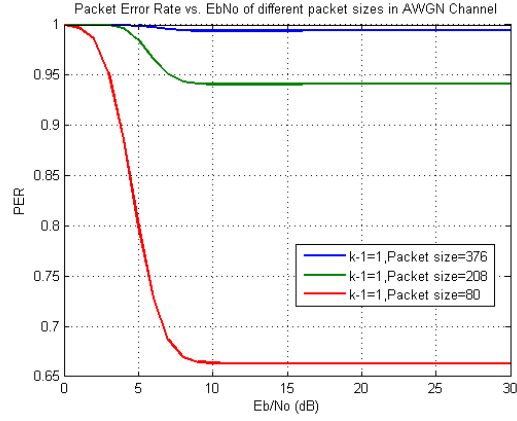
Figure 20 BER graphs of SFH-GMSK performance with 1 interfering user and with no interfering users.

## 5.2 PER Results

Based on the results of BER graphs shown in Figure 20, the corresponding PER graphs were generated using equation (31). Figure 21 shows the packet error rate of SFH-GMSK with 1 interfering user and with no interfering users in AWGN channel. It can be observed from this figure, that the PER increases as the packet size increases. Add to that, it can be seen that when there is no interfering users, the system promises nearly  $10^{-4}$  to no packet errors at 10dB and beyond. However, this is not the case when there is an interfering user, as the system promises approximately 66% error rate when packet size is 80 bits at 10dB and beyond. Also, for the same case with packet size 376, the PER graph shows that from 0 dB to 30 dB, each sent packet is most likely to be incorrect.



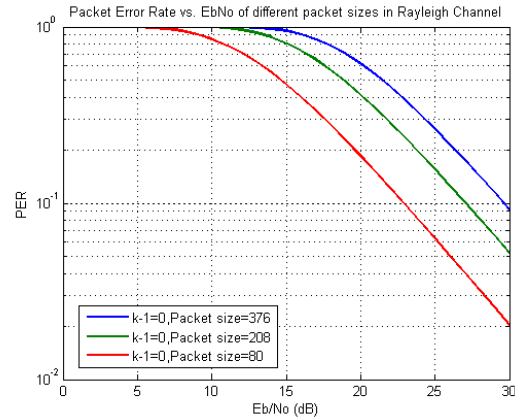
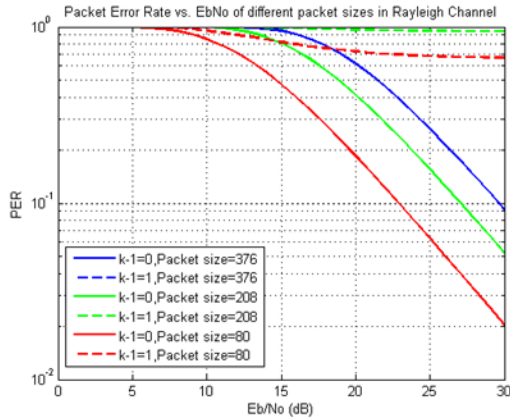
(a) AWGN, 1 Interfering User and No Interfering Users (b) AWGN, No Interfering User



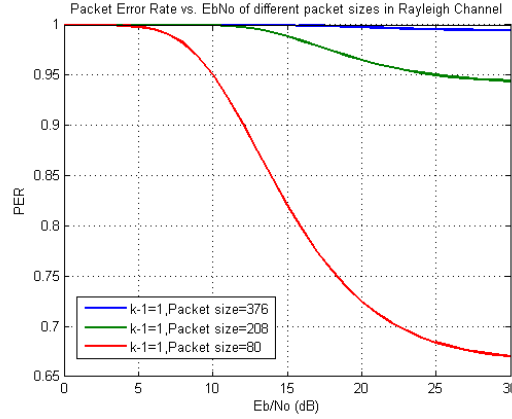
(c) AWGN, 1 Interfering User

Figure 21 PER graphs of SFH-GMSK performance in AWGN channel.

Figure 22 shows the packet error rate of SFH-GMSK with 1 interfering user and with no interfering users in slow and flat Rayleigh channel. Similar to the performance trend in AWGN channel, it can be observed from this figure that the PER increases as the packet size increases. Moreover, it can be seen that when there is no interfering users, the system does not offer low packet error rates over the studied Eb/No range. On the same note, the system performs even worst when there is an interfering user in the same spectrum.



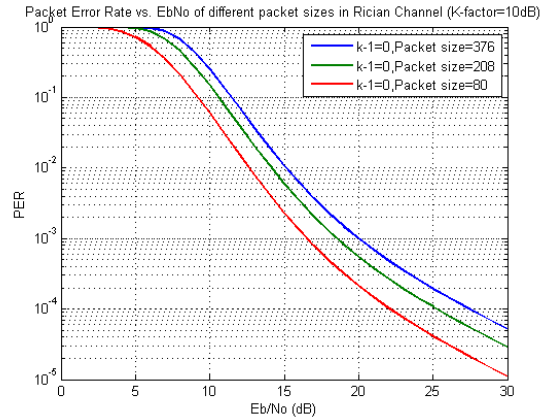
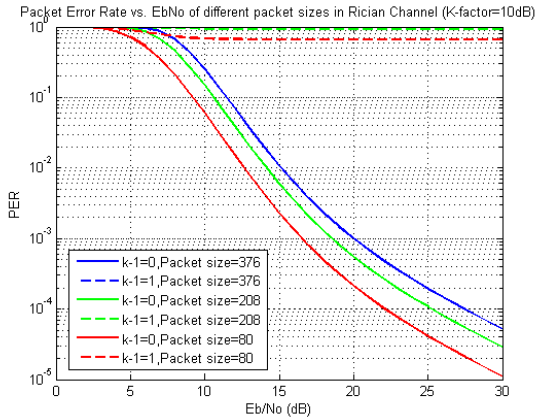
(a) Rayleigh, 1 Interfering User and No Interfering Users (b) Rayleigh, No Interfering User



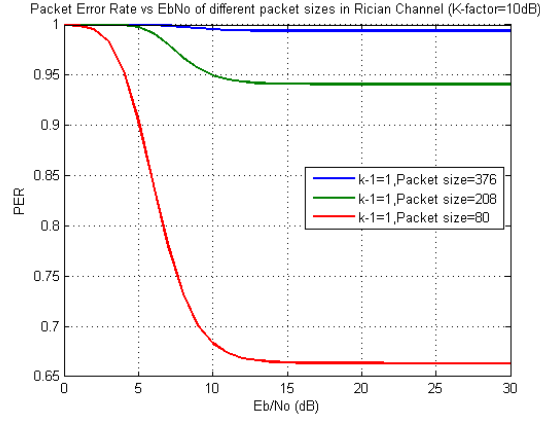
(c) Rayleigh, 1 Interfering User

Figure 22 PER graphs of SFH-GMSK performance in Rayleigh channel.

Figure 23 shows the packet error rate of SFH-GMSK with one interfering user and with no interfering users in slow and flat Rician fading channel with K-factor=10dB. Also, it can be seen that the PER increases as the packet size increases. In addition, it can be seen that when there is no interfering users, the system promises  $10^{-1}$  to  $10^{-4}$  packet errors for all packet sizes at nearly 10dB and beyond. However, this is not the case when there is an interfering user, as the system promises around 66% error rate when packet size is 80 bits at 15dB and beyond. Also, for the same case with packet size 376, the PER graph shows that from 0 dB to 30 dB, each sent packet is most likely to be incorrect.

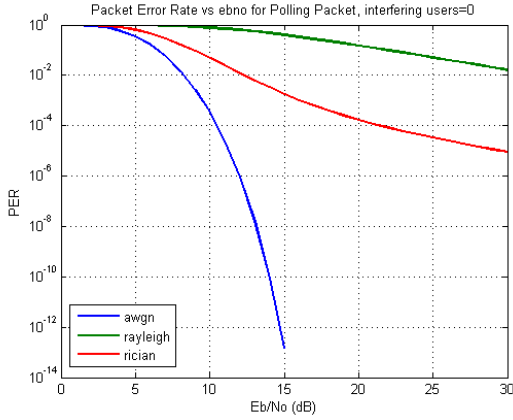


(a) Rician with K=10dB, interfering user and No Interfering (b) Rician with K=10dB, No interfering user

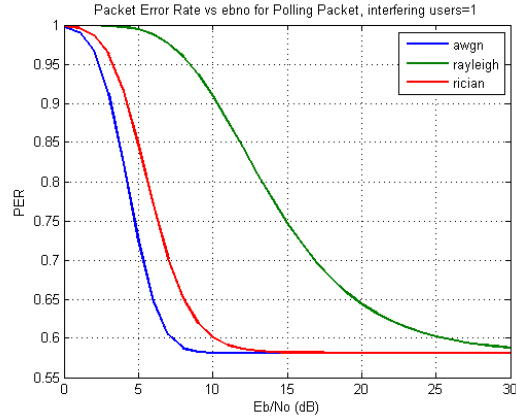


(c) Rician with K-factor=10dB, 1 Interfering User  
Figure 23 PER graphs of SFH-GMSK performance in Rician channel.

Figure 24 shows the packet error rate of the BLE polling packets (SFH-GMSK) with one interfering user and with no interfering users in AWGN, slow and flat Rayleigh channel and slow and flat Rician channel with K-factor=10dB. It can be observed from this figure that the PER is lowest at AWGN channel and highest at Rayleigh channel. Also, it can be seen that the performance of the system decreases sharply in the case of interfering users.



(a) Polling Packets, No Interfering User



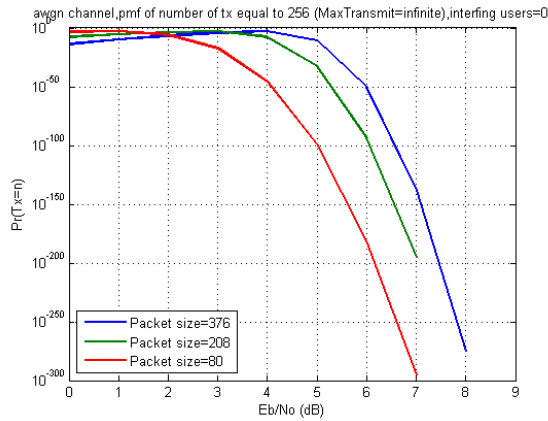
(b) Polling Packets, 1 Interfering User

Figure 24 PER graphs of polling packets with 1 interfering user and with no interfering users in AWGN, flat Rayleigh and flat Rician (K-factor=10dB) channels.

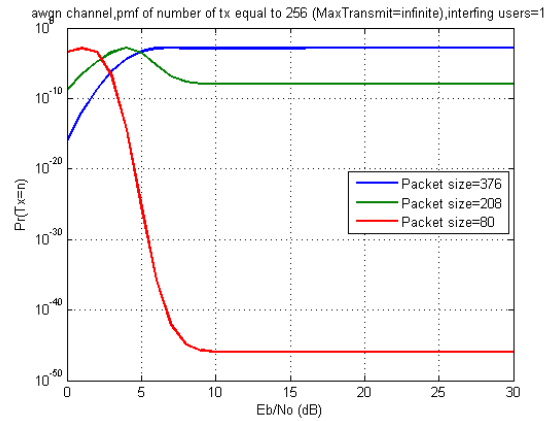
### 5.3 Average Packet Transmissions Results

Figure 25 shows the probability mass functions (pmfs) of required packet transmissions when the number of transmissions is 256, but not limited to it. These figures are generated from equation 32. It can be noticed that the probability of needing to send 256 transmissions to successfully transmit a packet gets lower with increasing Eb/No in all investigated channels. Hence, with more Eb/No, fewer transmissions are required. This is logical because the receiver can decode the message more efficiently despite the noisy environment. On the other hand,

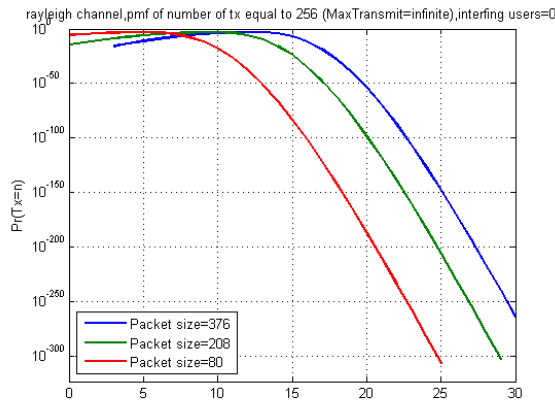
when there is an interference from coexisting system, the performance drops by roughly a factor of 6.



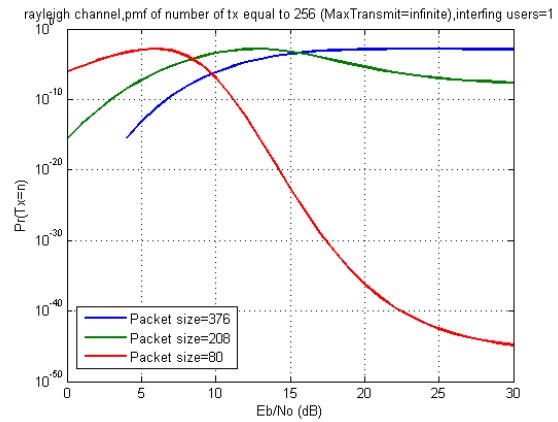
(a) AWGN, No Interfering User



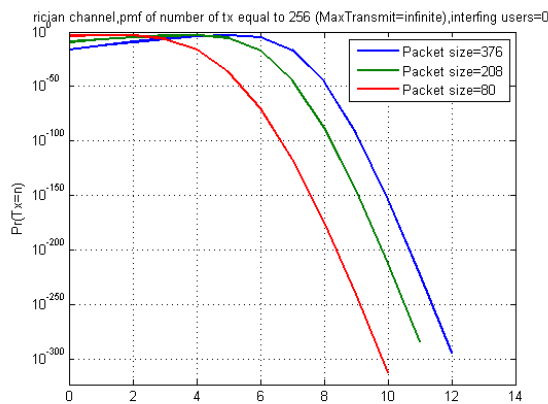
(b) AWGN, 1 Interfering User



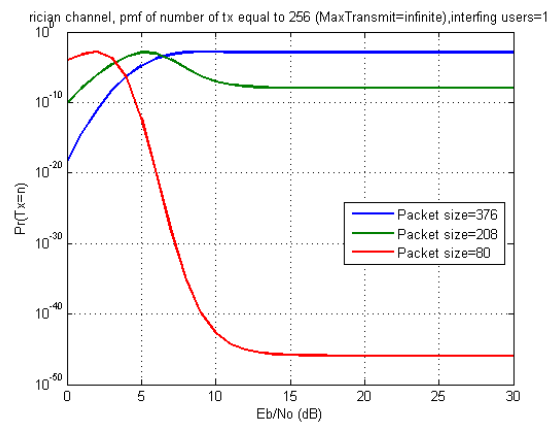
(c) Rayleigh, No Interfering User



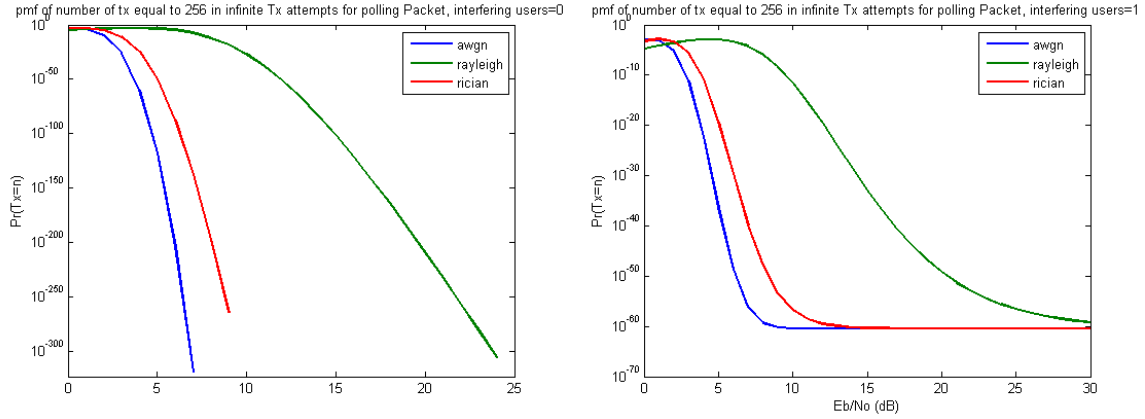
(d) Rayleigh, 1 Interfering User



(e) Rician with K=10dB, No Interfering User



(f) Rician with K=10dB, 1 Interfering User



(g) Polling Packets, No Interfering User

(h) Polling Packets, No Interfering User

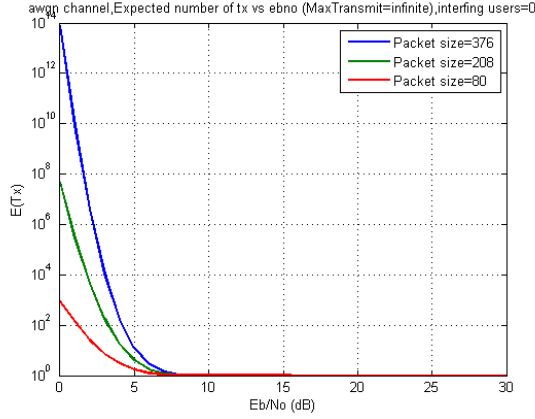
Figure 25 PMFs of number of transmission equal to 256 (MaxTransmit=infinite)

Figure 26 illustrates the average packet transmissions required when the number of transmissions is 256, but not limited to it. These figures are generated from equation 33. In Figure 26 a, it can be seen that at 0db Eb/No, the number of transmissions is very high. In reality it may reach to infinity. Then, with rising Eb/No, the number of average packet transmissions decreases until it reaches 1 transmission only on 11dB and beyond. In Figure 26 b, it can be seen that at 0db Eb/No, the number of transmissions is about  $10^{16}$ , however, in reality it may reach to infinity. Moreover, it can be seen that the number of average packet transmissions decreases until it reaches 30 transmissions for packet with 80 bits, 60 transmissions for packet with 208 bits and 130 transmissions for packet with 376 bits from 7dB and beyond.

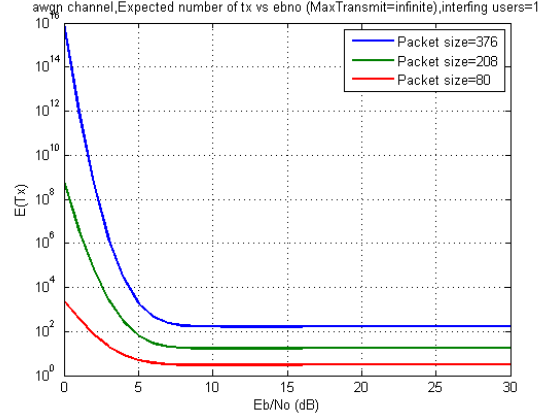
In Figure 26 c, it can be seen that at 0db Eb/No, the number of transmissions is very high. The number of average packet transmission reaches 2 transmissions for packet with 80 bits, 4 transmissions for packet with 208 bits and 6 transmissions for packet with 376 bits from. In Figure 26 d, it can be observed that the performance is much worst. Moreover, it can be seen that the number of average packet transmissions decreases until it reaches 30 transmissions for packet with 80 bits, 60 transmissions for packet with 208 bits and 130 transmissions for packet with 376 bits from 27dB and beyond.

The average packet transmission required by the system in Rician channel is presented in Figure 26 e and d. It can be seen that the number of transmissions is extremely high, but it drops sharply with higher Eb/No. The number of average packet transmission reaches 1 only when the Eb/No is from 13 dB and beyond. In Figure 26 f, it can be observed that the performance is much worst. Moreover, it can be seen that the number of average packet transmissions decreases until it reaches 30 transmissions for packet with 80 bits, 60 transmissions for packet with 208 bits and 130 transmissions for packet with 376 bits from 12 dB and beyond.

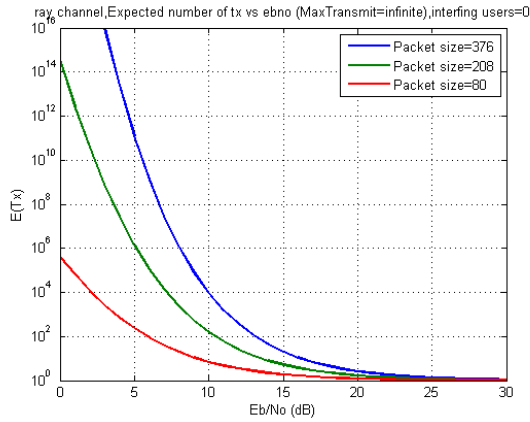
Finally, the expected number of polling packet transmission per Eb/No in AWGN channel, slow and flat Rayleigh fading channel and slow and flat Rician fading channel is presented in Figure 26 g and h. It can be seen that less retransmissions are required in AWGN channel, while, many retransmissions are required in the Rayleigh channels case.



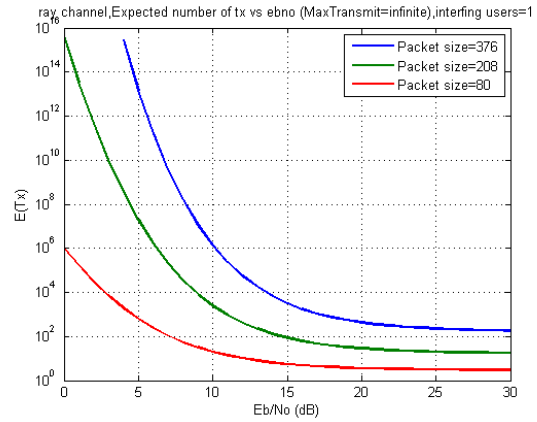
(a) AWGN, No Interfering User



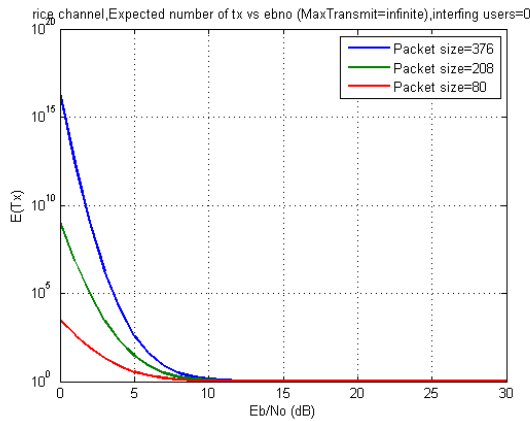
(b) AWGN, 1 Interfering User



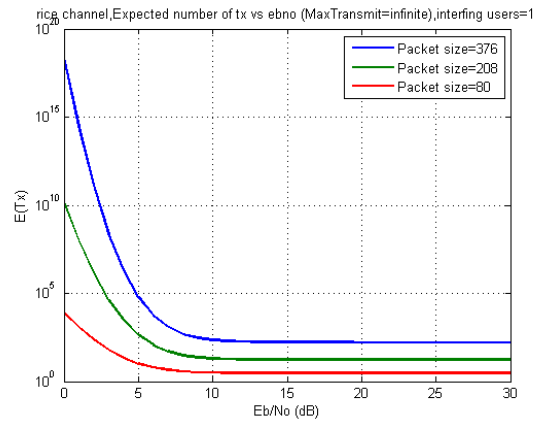
(c) Rayleigh, No Interfering User



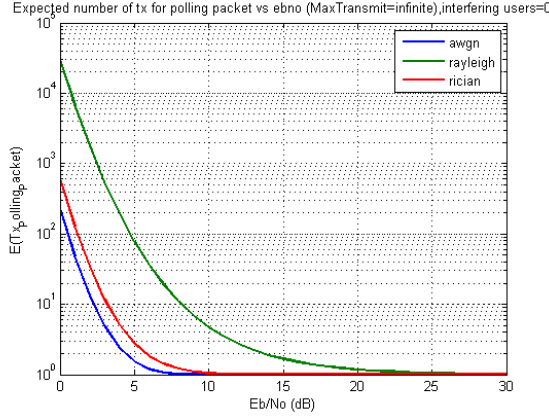
(d) Rayleigh, 1 Interfering User



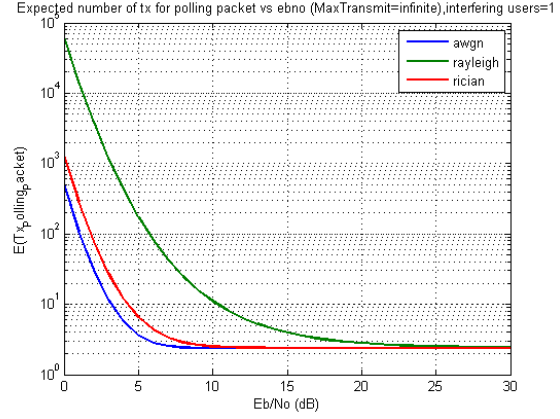
(e) Rician with K=10dB, No Interfering User



(f) Rician with K=10dB, 1 Interfering User



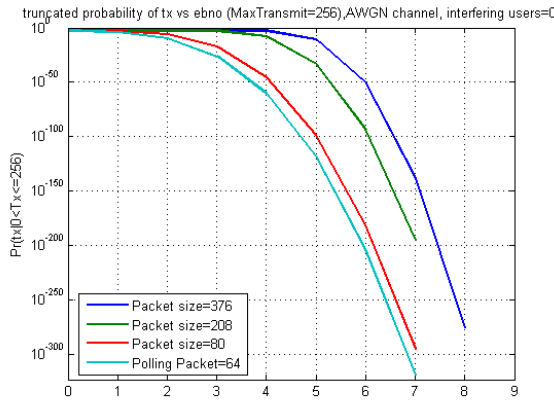
(g) Polling Packets, No Interfering User



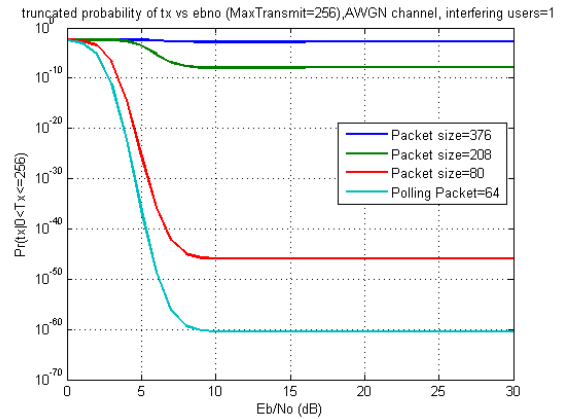
(h) Polling Packets, No Interfering User

Figure 26 Expected number of required transmissions

Figure 25 and Figure 26 show the probability mass functions and the expected value of the required packet transmissions when the number of allowed transmission is unlimited at the BLE module. However, in real life, the number of transmissions most likely to be limited to a certain number. As discussed previously in section 4.6.1, the MaxTransmit parameter is responsible for defining the maximum number of allowed transmissions. Also, as discussed in section 4.6.3, a truncated probability that finds the probability of having successful transmission during 256 attempts was developed and shown in equation (34). Equation (34) was used to generate the results shown in Figure 27.

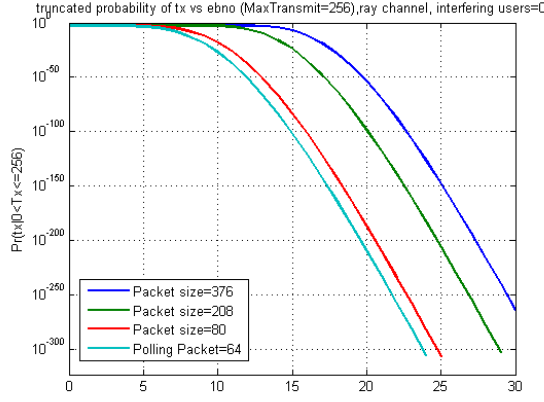


(a) AWGN, No Interfering User

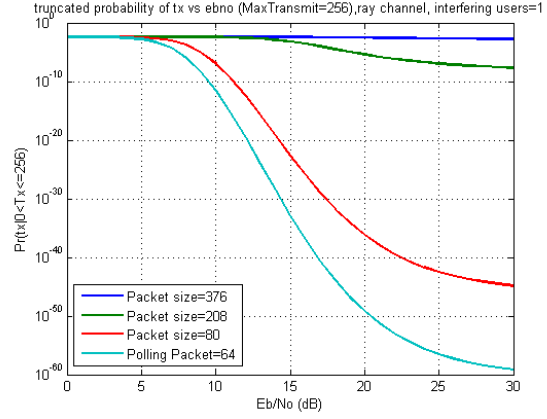


(b) AWGN, 1 Interfering User

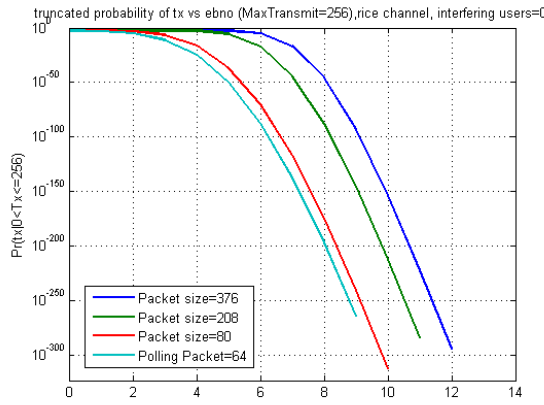




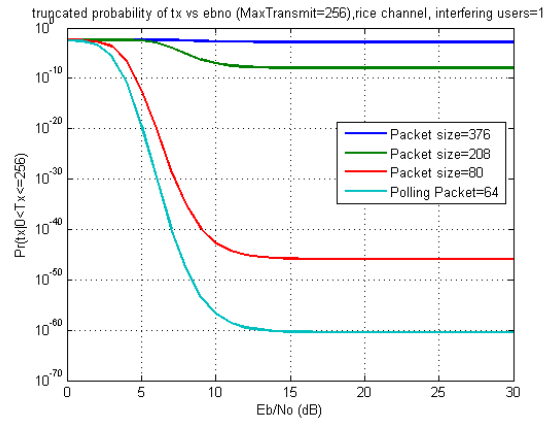
(c) Rayleigh, No Interfering User



(d) Rayleigh, 1 Interfering User



(e) Rician with K-factor=10dB, No Interfering User



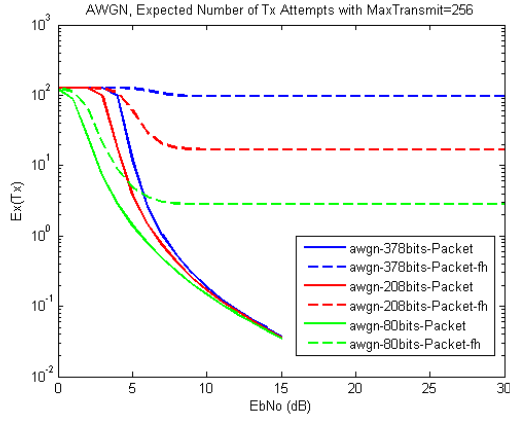
(f) Rician with K-factor=10dB, 1 Interfering User

Figure 27 Truncated probability of transmission when MaxTransmit is set to 256

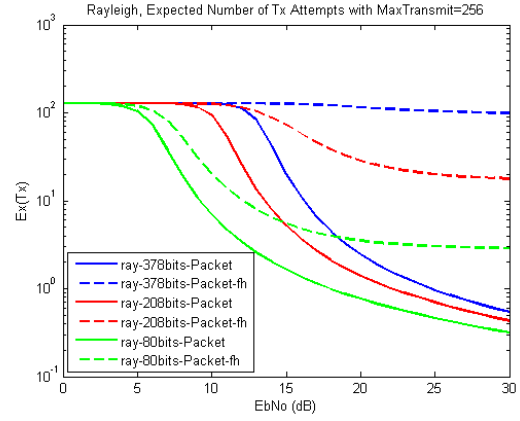
Figure 27 (a) shows that the probability of having unsuccessful transmission decreases sharply with increasing  $E_b/N_0$  within the allowed range of transmission attempts. Also, it shows that with less packet size, the probability of success is higher. Figure 27 (b) presents the truncated probability of transmission attempts when there is an interfering user. In this case, the performance decreases dramatically. It also can be seen that the probability of packets with size 376 bits have high probability that more than 256 transmission is needed. In both Figure 27 (a) and (b), the channel studied is simple AWGN.

Figure 27 (c) and Figure 27 (e) show similar trend to that of Figure 27 (a). However, they give worst response as the channels are more severe. The exact thing can be said about Figure 27 (d) and Figure 27 (f) in relation to Figure 27 (b).

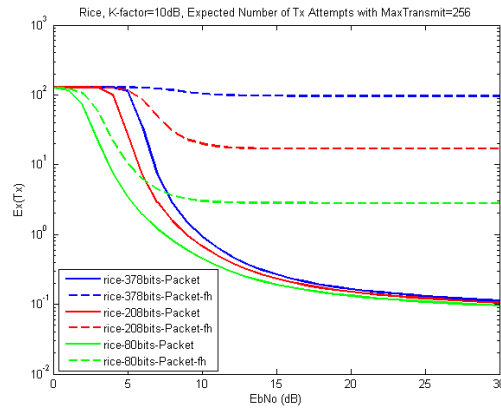
After finding the pmfs of the packet transmission attempts, it is logical to calculate the expected number of packet transmissions. Equation (35) was used get (a), (b) and (c) of Figure 28 and (a), (b) and (c) of Figure 29.



(a) AWGN

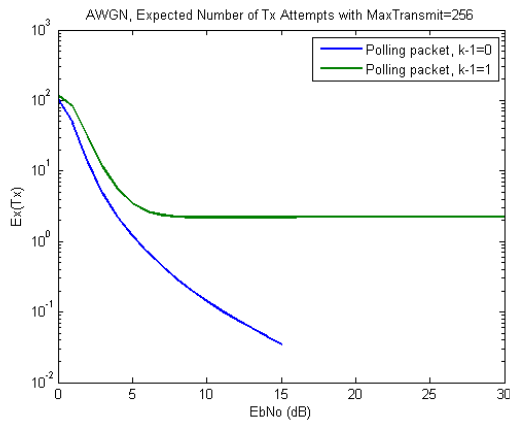


(b) Rayleigh

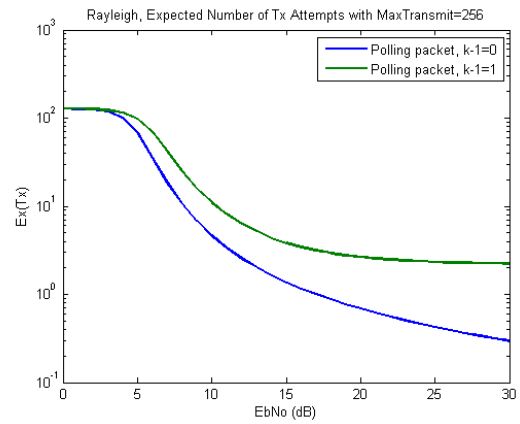


(c) Rician with K-factor=10dB

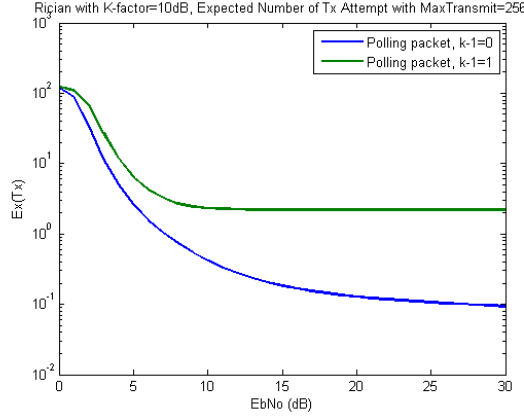
Figure 28 Expected number of required transmissions when MaxTransmit is set to 256.



(a) AWGN



(b) Rayleigh



(c) Rician with K-factor=10dB

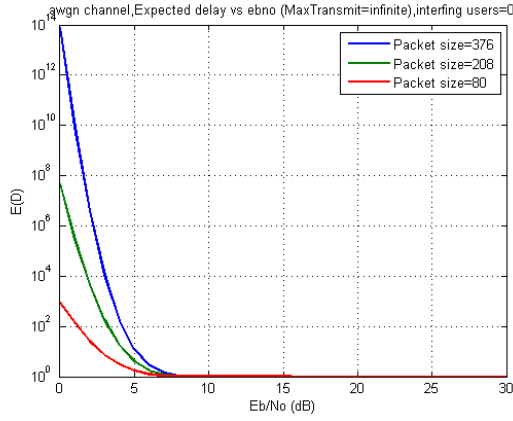
Figure 29 Expected number of required polling transmissions when MaxTransmit is set to 256

In both Figure 28 and Figure 29, it can be seen that the average number of packet transmission is about 129 attempts when the  $E_b/N_0$  is 0 dB. In reality, this number could reach 256, which is the number set in MaxTransmit parameter. It also can be seen that using large size packets affect the performance badly. Therefore, the proposed system should use the smallest packet size possible (80 bits).

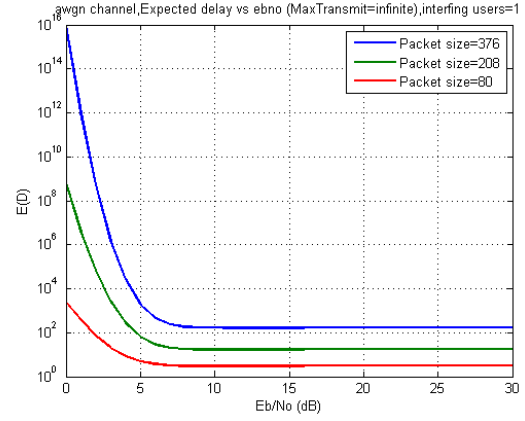
## 5.4 Average Packet Delay Results

After analyzing the expected number of packet transmission required to get a correct packet, the resultant packet delay is calculated. Packet delay follows the same probability distribution as average packet transmission attempts. Therefore, using equations (37) and (38), Figure 30 and Figure 31 were plotted.

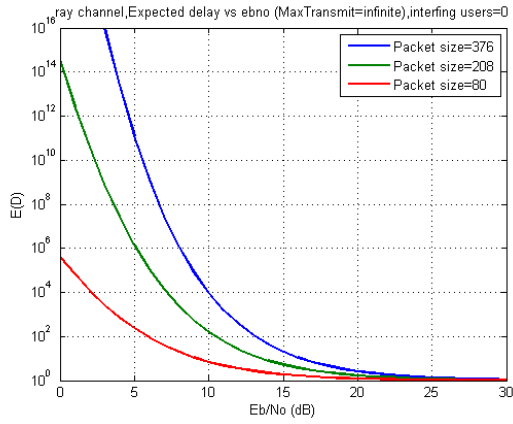
Figure 30 shows the average packet delay for packet sizes 80 bits, 208 bits and 376 bits with  $E_b/N_0$  range from 0 dB to 30 dB when the MaxTransmit parameter is set to infinity ( $\infty$ ). It can be seen that the delay drops sharply in the first 6 dBs in AWGN, first 20 dBs in Rayleigh and first 8 dBs in Rician with K-factor of 10 dB, in the case of no interfering user. The same trend can be observed in the interfering user graphs Figure 30(b), (d), (f) and (h), however, they have generally higher average packet delay.



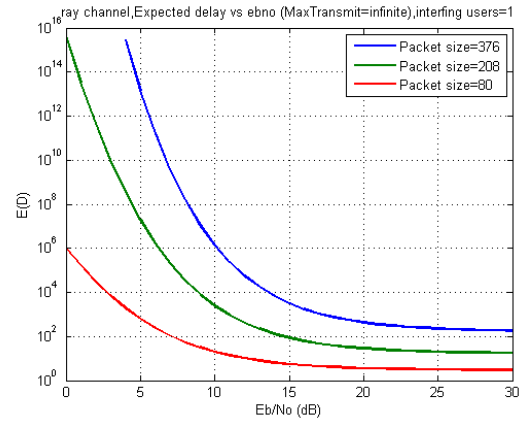
(a) AWGN, No Interfering User



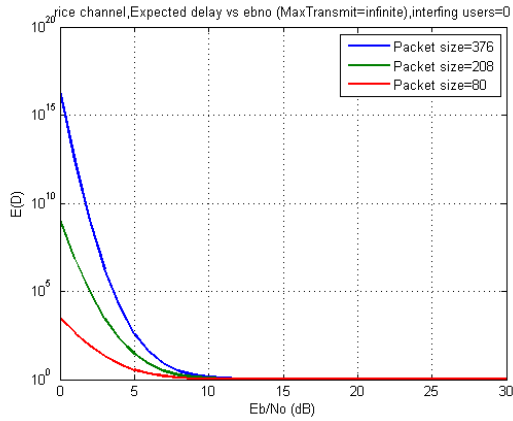
(b) AWGN, 1 Interfering User



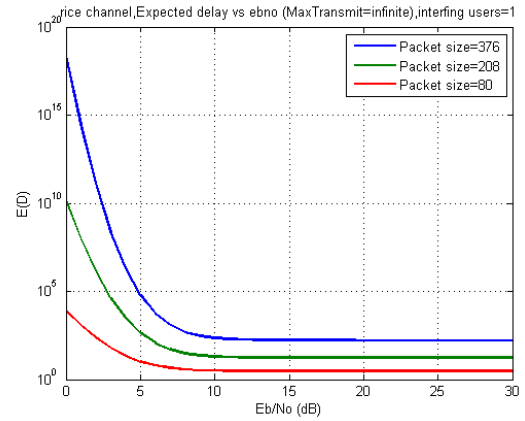
(c) Rayleigh, No Interfering User



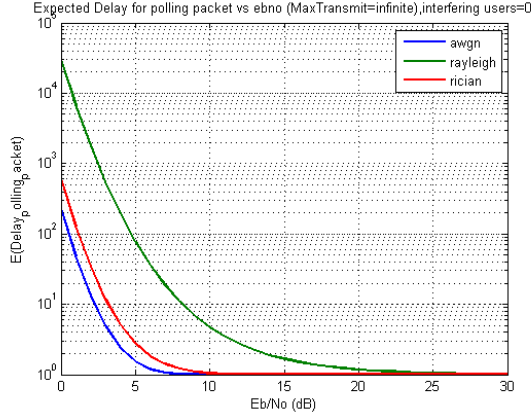
(d) Rayleigh, 1 Interfering User



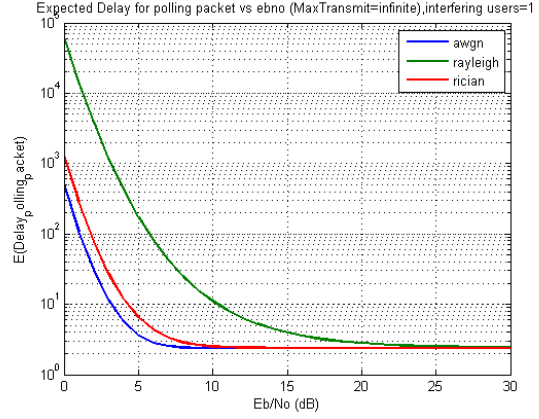
(e) Rician with K=10dB, No Interfering User



(f) Rician with K=10dB, 1 Interfering User



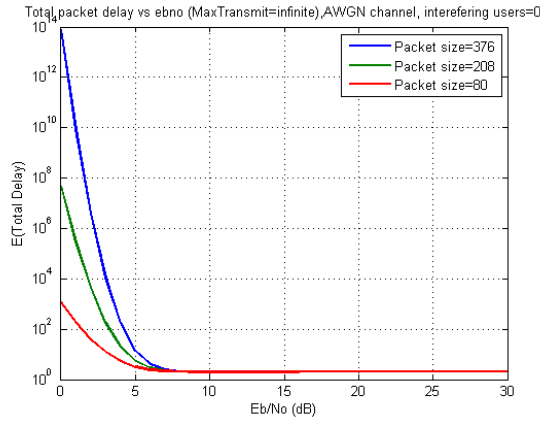
(g) Polling Packets, No Interfering User



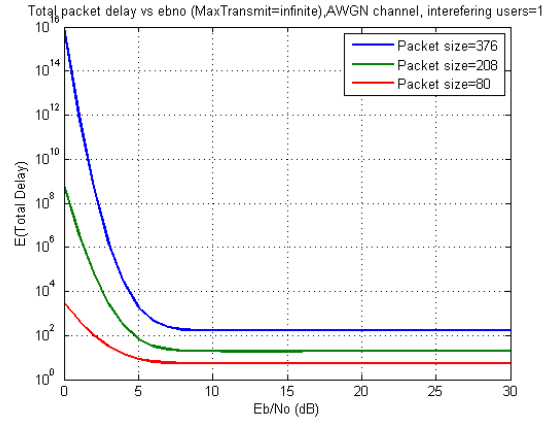
(h) Polling Packets, No Interfering User

Figure 30 Average packet delay

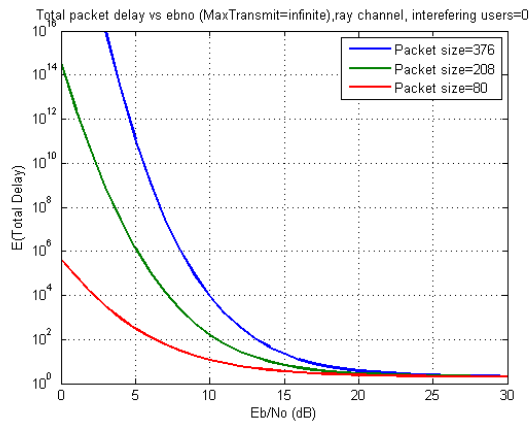
Figure 31 shows the average total packet delay for packet sizes 80 bits, 208 bits and 376 bits with Eb/No range from 0 dB to 30 dB when the MaxTransmit parameter is set to infinity ( $\infty$ ). It can be observed that it has the same trend as the graphs of Figure 30.



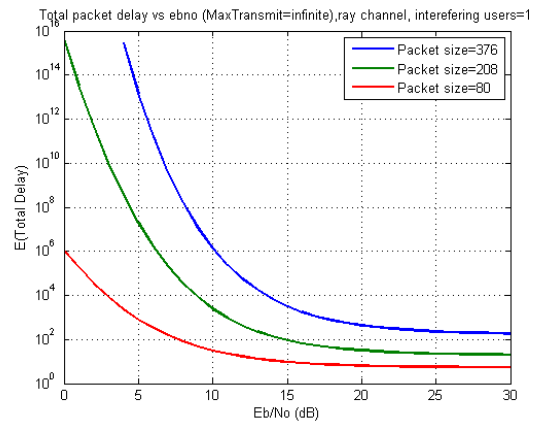
(a) AWGN, No Interfering User



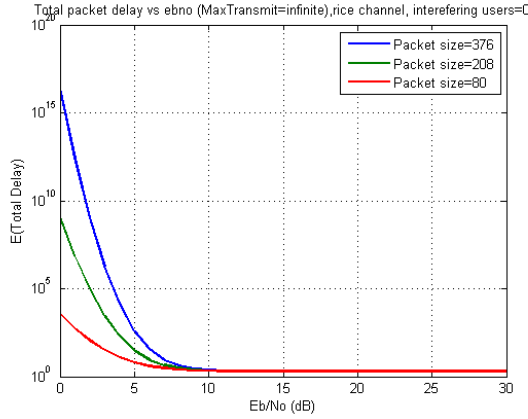
(b) AWGN, 1 Interfering User



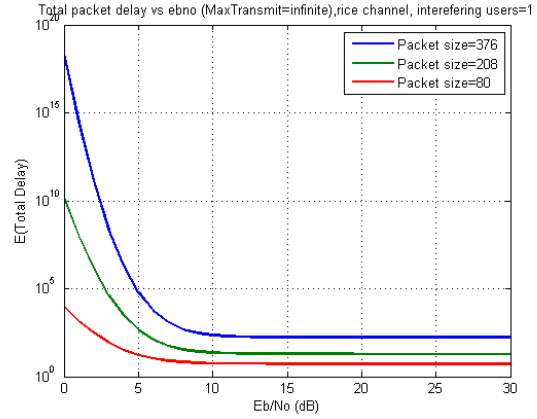
(c) Rayleigh, No Interfering User



(d) Rayleigh, 1 Interfering User



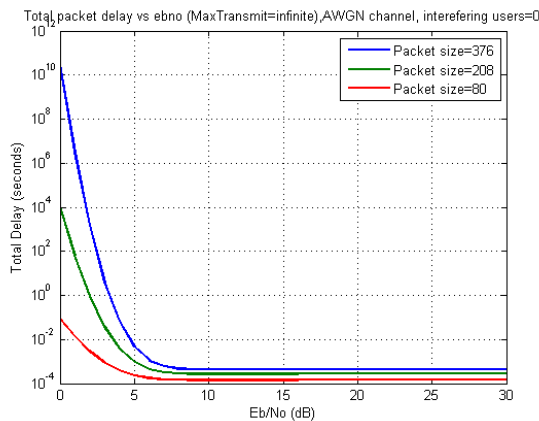
(e) Rician with  $K=10\text{dB}$ , No Interfering User



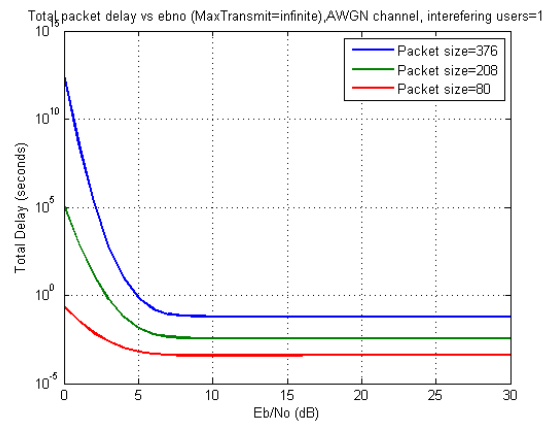
(f) Rician with  $K=10\text{dB}$ , 1 Interfering User

Figure 31 Total packet delay

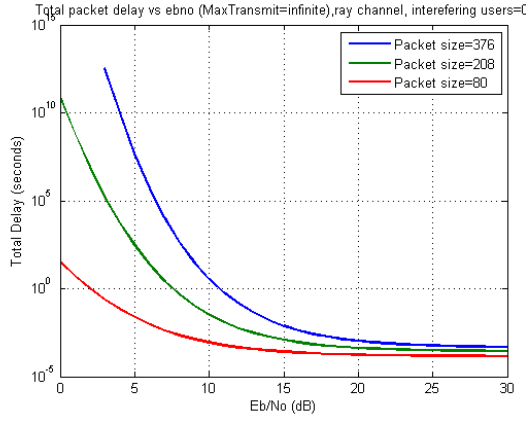
Figure 32 shows the average total packet delay in seconds for packet sizes 80 bits, 208 bits and 376 bits with  $E_b/N_0$  range from 0 dB to 30 dB when the MaxTransmit parameter is set to infinity ( $\infty$ ). In Figure 32 (a), it can be seen that the total delay is about 500 us for 376 bits packet, about 260 us for 208 bits packet, and slightly above 100 us for 80 bits packet. This is much better than the 28 ms in HIT system. In Figure 32 (b), it can be seen that the total delay is about 1 ms for 376 bits packet, about 10 ms for 208 bits packet, and about 1 ms for 80 bits packet. In the case of interference, it can be seen that the system gives better performance than the HIT system in AWGN channel, only when the packet size is less than 367. Similar trends can be observed for the other graphs Figure 32 (c), Figure 32 (d), Figure 32 (e) and Figure 32 (f). However, they have generally higher delays as Rayleigh and Rician channels are more severe.



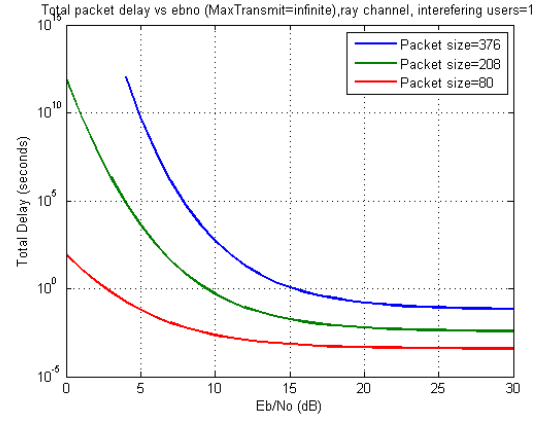
(a) AWGN, No Interfering User



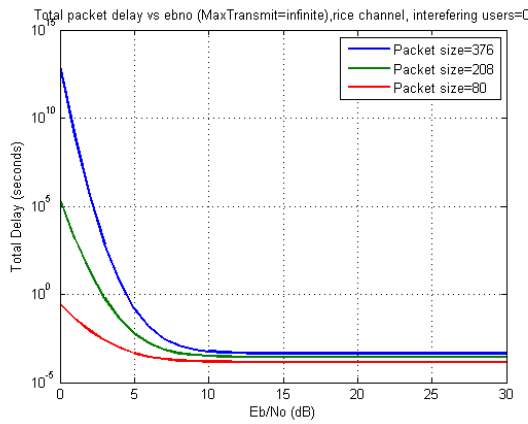
(b) AWGN, 1 Interfering User



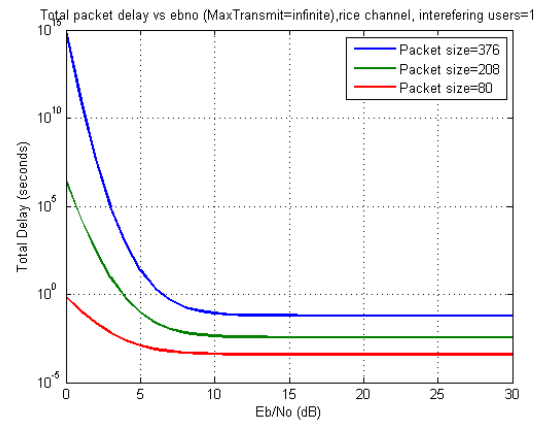
(c) Rayleigh, No Interfering User



(d) Rayleigh, 1 Interfering User



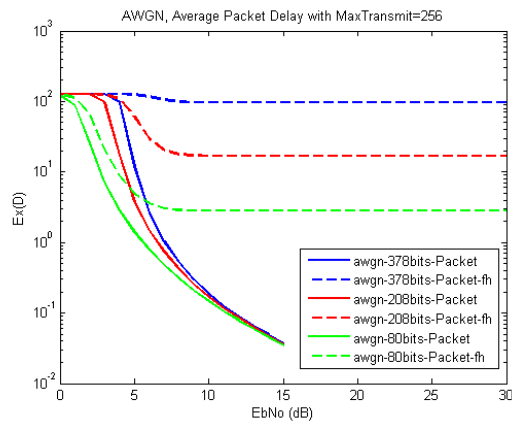
(e) Rician with K=10dB, No Interfering User



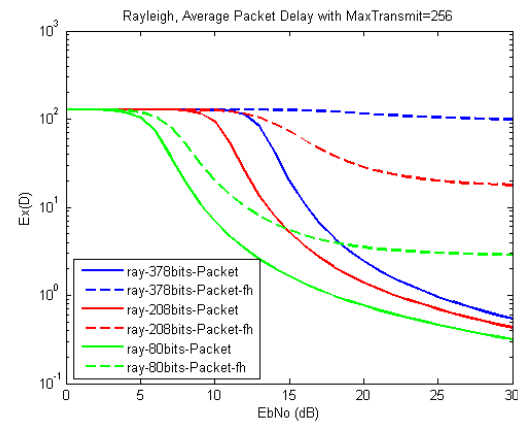
(f) Rician with K=10dB, 1 Interfering User

Figure 32 Total Delay for unlimited MaxTransmit in seconds

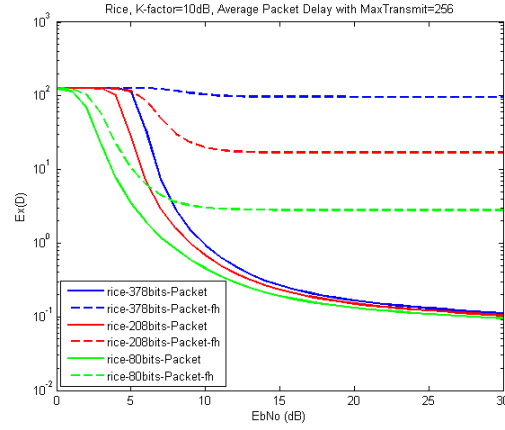
After analyzing the average packet delay in the case of unlimited allowed transmissions, the average packet delay of limited transmissions (256) scenario is studied. The delay starts at 129 time unit at 0 dB and then drops with increasing signal power ( $E_b/N_0$ ). Figure 33 and Figure 34 are generated from equation 40. In here also, it can be seen that better delay responses are seen for small sized packets and less harsh channels.



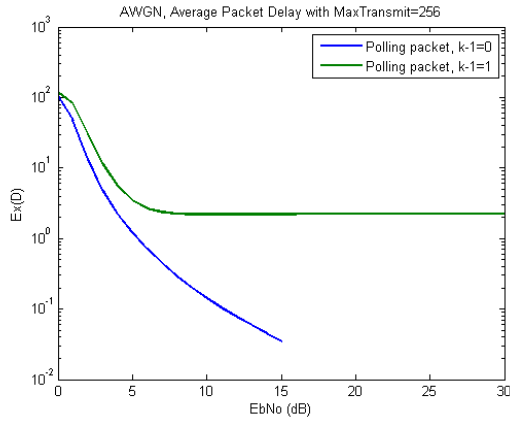
(a) AWGN



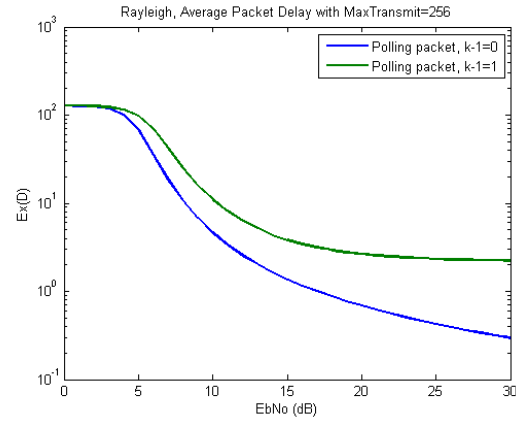
(b) Rayleigh



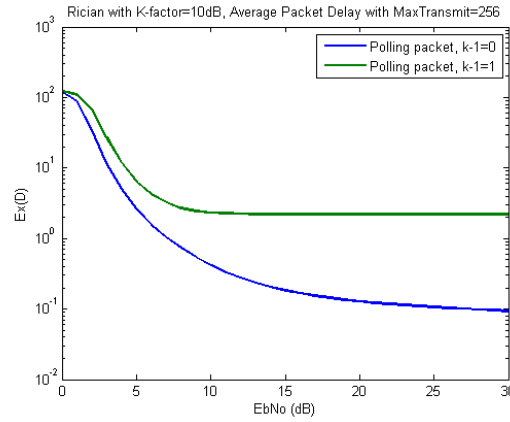
(c) Rician with K-factor=10dB  
Figure 33 Average packet delay with MaxTransmit=256



(a) AWGN



(b) Rayleigh



(c) Rician with K-factor=10dB  
Figure 34 Average polling packet delay with MaxTransmit=256

Then Figure 35 was generated by the use of equation 38, where the results of Figure 33 and Figure 34 are added together to get the total delay.



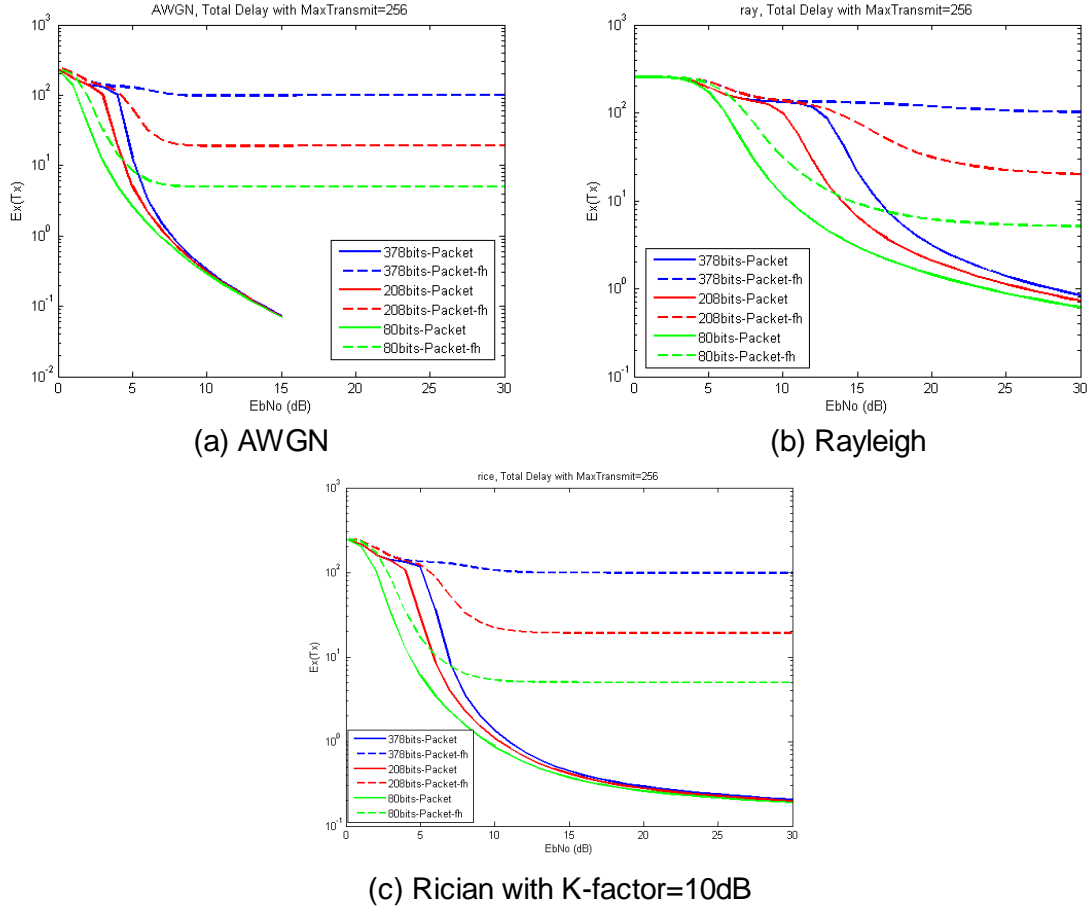


Figure 35 Total packet delay with MaxTransmit=256

Figure 36 shows the average total packet delay in seconds for packet sizes 80 bits, 208 bits and 376 bits with  $E_b/N_0$  range from 0 dB to 30 dB when the MaxTransmit parameter is set to 256. In Figure 36 (a), it can be seen that the total delay at 15 dB is about 16  $\mu$ s for 376 bits packet, about 10  $\mu$ s for 208 bits packet, and about 4  $\mu$ s for 80 bits packet. However, for the case of the existence of an interfering user, the total delay at 15 dB is about 36 ms for 376 bits packet, about 4 ms for 208 bits packet, and about 363  $\mu$ s for 80 bits packet. In Figure 36 (b), it can be seen that the total delay at 30 dB is about 37 ms for 376 bits packet, about 4 ms for 208 bits packet, and about 370  $\mu$ s for 80 bits packet. However, for the case of no interfering user, the total delay at 30 dB is about 220  $\mu$ s for 376 bits packet, about 100  $\mu$ s for 208 bits packet, and about 45  $\mu$ s for 80 bits packet. In Figure 36 (c), it can be seen that the total delay at 30 dB is about 37 ms for 376 bits packet, about 4 ms for 208 bits packet, and about 363  $\mu$ s for 80 bits packet. However, for the case of no interfering user, the total delay at 30 dB is about 48  $\mu$ s for 376 bits packet, about 28  $\mu$ s for 208 bits packet, and about 14  $\mu$ s for 80 bits packet.

Hence, it can be seen here as well that the choice of limited and limited sized packets decreases the latency of the system as well as reducing the number of re-transmissions.

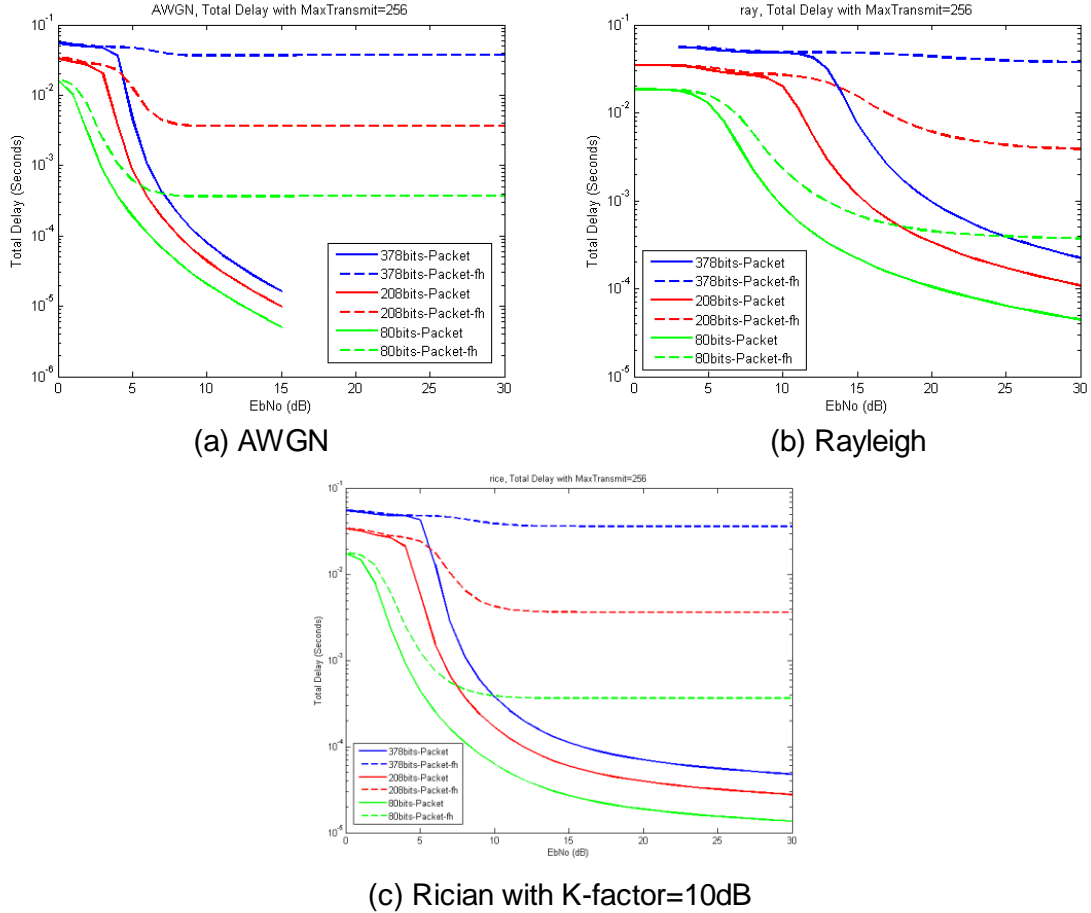
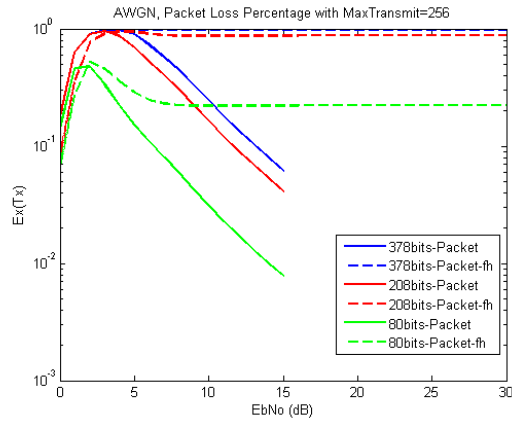


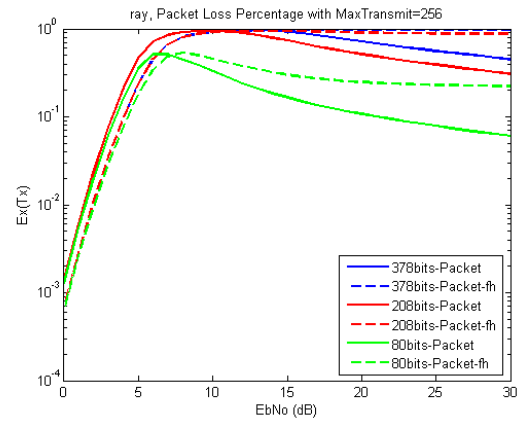
Figure 36 Total packet delay with MaxTransmit=256 in seconds

## 5.5 Packet Loss Percentage Results

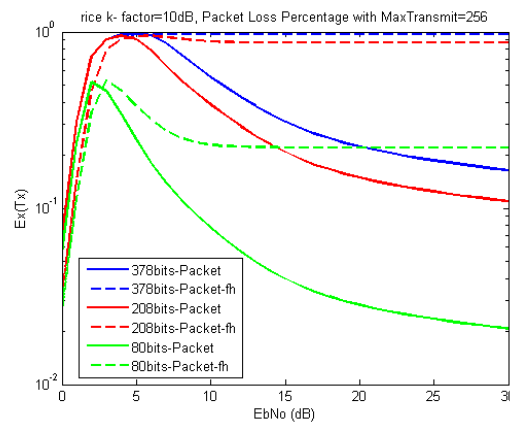
Figure 37 shows the expected packet loss percentage in the case of limited transmissions to 256 attempts. Figure 37 has been generated from Equation (41). The graphs show that at 0 dB Eb/No, the percentage of packet loss is lower than the one at higher Eb/No; the reason for this is that equation 41 subtracts the number of received data packets from the number of transmitted data packets, and then, divides it by the number of transmitted data packets. This gives the percentage of packet loss but with-out fairness. The fairness is lost because at each Eb/No, the number of transmitted data packets drops significantly. Moreover, the hump that can be seen at the first dBs of the Eb/No range is caused by that the polling packets (received data) and data packets (transmitted data) have different trend in Eb/No range.



(a) AWGN



(b) Rayleigh



(c) Rician with K-factor=10dB

Figure 37 Packet loss percentage with MaxTransmit=256

## 6 Conclusion and Future Work

In this Master Thesis, all the research questions set have been answered. The first research question was answered by studying the state-of-the-art sport safety systems. It was found that there is only one commercially available system and it is called HIT. This system is used in both Riddell InSite and Riddell SRS. These systems pose some advantages and disadvantages. The second research question was answered by developing several justified requirements that adopt the advantages and solve the disadvantages of Riddell InSite and Riddell SRS systems. After that, the third research question was answered by discussing the most suitable sensor for players' collisions impact estimation. Accelerometer was selected because it is low cost, small in size, and has high measurement range. The fourth question was related to the applicable wireless technologies and their grading. This has been answered by briefly describing the BLE, ZigBee and Dash7 technologies, and then benchmarking them with the developed system requirements. BLE was the overall best performer. Then, the final research question was answered by evaluating the BLE performance by measuring the BER, PER, average packet transmissions, average packet delay, total packet delay and packet loss percentage.

From the System Results and Analysis chapter (5), it can be observed that the BLE system with unlimited "MaxTransmit" can deliver a successful packet in 1 to 60 transmission attempts, when there is no interference. If there is interference, the number of required transmission attempts increase sharply to be 10 to 7000. A similar trend can be seen in the total packet delay graphs. The total packet delay is between 100 us to 8 ms, when there is no interference. However, if there is interfering system in the spectrum, the total delay increases to be 400 us to 1 s. On the other hand, the system with limited "MaxTransmit" can deliver successful packet in 1 to 3 attempts when there is no interference. Contrary to that, if there is interference, the BLE system can deliver a successful packet in 3 to 128 attempts. Also, the total packet delay is between 5 us to 8 ms in the case of no interference, and between 400 us to 50 ms in the case of interference. All the mentioned results are taken from 15 dB (Eb/No) SNR point.

Therefore, it can be concluded that the proposed system is low cost, has same network size, small and light, can monitor both head and chest impacts, gives decent throughput (max. 1 Mbps), can monitor up to 1000 players, and has low power consumption when compared to HIT products. Also, it has good overall performance in all the studied scenarios, when the packet size is small, signal-to-noise ratio (Eb/No) is above 15 dB, and MaxTransmit parameter is limited. Hence, this system may ultimately lead to reduction in total severe injuries, increased player career duration and considerable savings for clubs as the players will be diagnosed with their injuries at an early stage.

Finally, as a future work, the proposed system can be developed into a real prototype and then actual measurements in an ice rink can be made to observe the actual functionality.

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